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PIONEERING PROGRESS

AMERICAN SCIENCE, TECHNOLOGY, AND INNOVATION POLICY

WILLIAM B. BONVILLIAN

The MIT Press
Cambridge, Massachusetts
London, England

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William B. Bonvillian
Cambridge, Massachusetts, January 2024

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INTRODUCTION: THE WHY OF THIS BOOK

Why study science and technology policy? The role of technological advancement requires a rethink in light of the shifting world of the early twenty-first century.

The world seemed much clearer in 1989. Although the world was still armed to the teeth from decades of Cold War, in a seemingly miraculous way, the war was fading away. The Berlin Wall came down, signaling not just a thaw but the end of that long confrontation that had so dominated forty years of history. It felt as though the communist ideology was simply fading away from its own inherent inefficiency. The Iron Curtain didn't just open; it was shattered. The US was the surviving, globally dominant actor, with military, political and economic primacy. That summer, Francis Fukayama declared the "end of history." Communism was over, and a clear future centering around democracy and capitalism appeared assured.

From an economic perspective, the US was beginning to revive from a long period of low productivity and growth. By 1991, the country was at the center of a vast innovation wave around computing and information technology (IT) that would dominate world economic attention for decades to come. That decade saw strong economic growth, a jump in productivity, and corresponding widespread economic developments that benefited every economic level of American society. Globalization was rapidly imposing its will on the world economy, a seemingly inevitable force no more likely to be turned back than the tide.

It was during the 1990s that I began teaching courses on science and technology policy and innovation systems to try to explain how this advance evolved and how to spur more of it. Three decades later, much of this ground has shifted. What is the new rationale for science and technology policy and the innovation behind it? Let's look first at the shift.

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CHINA SHOCK

China had been welcomed into the world economy and US markets with open arms by President Bill Clinton. China's amazing industrial growth since 1989 was equaled only by US industrial growth in the decades before World War I. The country overtook US manufacturing output by 2011, was on a path to outinvest the US in research and development (R&D), and was hatching systematic plans to assume the leadership of every significant technology sector.

The optimistic hopes that the entry of capitalism would open China's political system toward democracy proved entirely misplaced. Instead, lower-cost manufactured goods from China swept aside tens of thousands of American factories in the Northeast and Midwest, throwing many communities into a declining economic spiral. The internet, widely thought to be a tool for new freedoms, instead became a tool for thought control. Rather than Western market capitalism, China developed a new brand of state capitalism and became the ascending economic power. And rather than embracing a world role, China was pulling back by 2019, shutting down open communication technologies, and beginning to stamp out technologies and technology leaders that might in any way challenge the power of its increasingly dictatorial state. The country's leaders chose greater political repression over opening its political system. And now we seem on the verge of another Cold War, with China organized around its own version of a communism that we thought had faded away.

The US government appears increasingly ready to confront this new colossus, but American business is not there, still locked into riches available from dependence on outsourced Chinese goods and potential opportunities in Chinese markets. It is a divided front. While China has experienced a declining growth rate since 2021, it remains a production powerhouse to be reckoned with.

CLIMATE SHOCK

Nature appeared to be conspiring against American ascendency as well, through climate change and the coronavirus pandemic. Climate disruption has finally become clearly visible with ever-more-powerful disasters resulting not from nature changing the climate itself but from human defiance of nature. Record-setting high temperatures are routine. Wildfires routinely sweep through most Western US states, costing lives and homes and creating a choking haze for much of the summer. Droughts, tornadoes, and hurricanes in other regions keep growing in intensity. There are still many so-called climate deniers, but nature is telling a different story.

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In the face of this, one of the two major political parties in the US has locked denial into its ideology. President Donald Trump's administration worked to dismantle many of the tools to confront climate change. Sir Nicholas Stern, the former chief economist of the World Bank, called climate change, and the world's corresponding failure to address it, "the greatest market failure in history."[1]

Even if the US got its policy act together, however, the country can't act alone. A growing sentiment of political isolationism growing among the US populace notwithstanding, climate demands global collaboration. And China's massive growth has made it the largest global emitter, larger than the US and Europe combined. How can we confront China's political oppression and collaborate on climate?

PANDEMIC SHOCK

COVID-19 was a nightmare waiting to happen; while much progress has been made across the world to reduce the threat of communicable diseases, HIV/AIDS was a signal of what was to come. After a series of communicable disease threats ranging from severe acute respiratory syndrome (SARS) to Middle East respiratory syndrome (MERS), a deadly coronavirus finally emerged at scale, originating in China and engulfing the planet within weeks at the beginning of 2020.

Although unanticipated by the political system and public, a pandemic had long been warned about by disease experts. Geographic distance once provided protections against disease spread, but the ease of worldwide travel and globalization of the world economy erased that barrier.

Our globalized economy profoundly contradicts sound public health practice. And there is profound market failure here, too: although the threat of pandemics requires intense global cooperation, the world has failed to build a sound public health network.[2] The budget for the World Health Organization, for example, is scrounged from many sources and is smaller than that that of a large hospital.

China's initial failure to control the virus in the Wuhan region looked at first like a Chernobyl moment, exposing the sorts of failures of totalitarian regimes that had earlier so undermined the credibility of the Soviet Union. But it turned out to be the American performance that looked pathetic. While China's determined lockdowns controlled the pandemic there for a time, the US became one of the hardest-hit nations, and its open lifestyle conspired with the virus to spread the disease. Public health authorities were unable to persuade some one-third of the independent-minded citizenry to get vaccinated once a vaccine was developed, or to adopt simple public health measures like masking and social distancing. The pandemic was politicized along party lines, and

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the president was in denial about the problem. The weaknesses in the once eminent but neglected US public health system became apparent to the world. It wasn't pretty, and it was deadly, resulting in more than a million American deaths.

Many Americans assume that COVID-19 is a once-in-a-lifetime event. After all, the previous global pandemic, the Spanish flu, occurred in 1919. But as already stated, the realities of global integration and travel make further infectious disease outbreaks likely.

All these shocks translated into economic disruption. The China shock played a significant role in economic declines in historic US manufacturing regions. Attempts by the administrations of Trump and then President Joe Biden to decouple from China's economy may lead to further disruption. Climate shock is only now beginning to have visible economic effects, but more are likely on the way. The coronavirus pandemic in 2020 led to massive unemployment in service sectors and the second-largest global recession in history. The US government stimulus in response to it furthered the high inflation of 2022–2023 and subsequent Federal Reserve (Fed) attempts to hold inflation in check by slowing the economy. All of this unfolded against a backdrop of the Great Recession of 2008–2009, when the interdependence and fragility of global financial institutions became clear to all. But there are other disruptions as well.

TECHNOLOGY AS DISRUPTOR

New IT technologies that emerged in the 1990s have proved to be a double-edged sword. The internet, initially viewed as a breakthrough for human connections, has ended up fragmenting our once-coherent media systems into political tribes. A manageable number of competing media outlets became thousands of competing outlets organized around affinity groups. As these groups became locked into certain social media platforms, their opinions hardened, and they became closed off to other perspectives. This tended to lock in political views and curtail communication across political lines. It has also amplified the news in unintended ways and spread disinformation. Some believe that these technologies themselves are undermining the country's ability to remain a cohesive nation.

DEMOCRACY ON THE EDGE

Applying these new tools, political consensus has been lost as right-wing populism has risen. The US had been playing a major role creating a new neoliberal consensus around democracy and markets, but this system has come under siege as centrists, once the mainstream of both political parties, find themselves caught between a violent

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right and an impassioned left. As one Texas politician once observed, "There's nothing in the middle of the road except yellow stripes and dead armadillos."[3]

Americans have chosen sides that keep pushing further and further away from each other. Far from being in ascendency after the end of the Cold War, US democracy itself has come under internal attack from right-wing populism, its processes victimized by an inability to obtain agreement between parties. The storming of the US Capitol by right-wing true believers on January 6, 2020, with the goal of overturning the results of the presidential election, was a symptom of the growing problem—one not limited to the US, but also found in Europe and South America.

SOCIAL DISRUPTION

The political disruption that has been taking place was in large part due to social disruption, much of it centered on a decline in American manufacturing, which shed nearly one-third of its workforce between 2000 and 2010 and shuttered 60,000 factories. International competition, principally from China, was the primary cause of these job losses.[4]

It is inequality, not economic convergence, that has increased in the US. There has been a growing and thriving upper class and upper-middle class, but a declining lower-middle class has found itself increasingly shunted into a growing lower-paid, lower-end services sector. Well-paid manufacturing jobs have been replaced by lower-paid service jobs; the US has been trading too many General Motors jobs for Dollar Store jobs. While tight labor markets since COVID-19 have been narrowing the inequality numbers, a major gap—including a psychological one—remains for the working class. Manufacturing productivity after 2007 has been at historically low levels, a signal of limited innovation and an inability to compete.

Where does technology policy stand in this conflicting morass? Why pursue it?

Technology in the service of the world hegemon is no longer the story. But technology policy turns out to be a toolset relevant to each of these strands. To cope with China's ascendancy as the dominant production economy means competing with a lower-cost, lower-wage economy. The only effective response is to apply innovation to raise productivity and efficiency and, therefore, the ability to compete. To cope with climate change requires an energy technology transformation, one in which technology innovation will be at a premium. Coping with a pandemic and other health threats required and will again require innovative new vaccine development and distribution systems. Coping with threats to democracy requires us to think through the societal ramifications of new technologies, including artificial intelligence (AI), before they reach scale, buying time to undertake compensating efforts.

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It also requires addressing the underlying social disruption and damage to the American working class. Improved economic well-being is mandatory—and achieving that requires renewed technology advancement. Yes, technology can be a threat. It can also be an economic opportunity, but the workforce must be ready to implement it. A new workforce education system is needed to put technology on the side of the workforce.[5]

Policy is critical to ensure that technology, a double-edged sword, remains on the *cutting* edge. Innovation and accompanying science and technology policy have a profound connection not only to our health and daily life, but also to society's economic growth and its corresponding ability to generate societal well-being and solve the profound societal challenges that we are confronting.

These economic and societal issues and challenges are deeply interrelated.

WHAT'S IN THIS BOOK?

This book focuses on science and technology policy. It examines the science and technology innovation system, including case studies on energy, computing, advanced manufacturing, and health sectors, with an emphasis on public policy and the US government's R&D role in that system. It reviews the foundations of innovation-based economic growth theory, innovation systems theory, and innovation organization theory, as well as the basic approaches to science and technology policy, enabling a sophisticated understanding of these areas. The book reviews a theory of direct and indirect economic factors in the innovation system, notes the innovation-based competitive and advanced manufacturing challenges now facing the US economy, reviews comparative efforts in other nations, studies the varied models for how federal science and technology mission agencies are organized, and explores the growth of public-private partnership models as a way for science agencies to pursue mission agendas. Emphasis is placed on examining the organization and role of medical science and energy innovation agencies and gaps in the health, energy, and advanced production innovation economic models. It explores how far innovation systems policy should go.

The book also examines industrial policy. It includes a review of the science and technology talent base, focused on the workforce as a factor in growth and the education approaches that support the workforce. This includes a discussion of the future of jobs and employment, given increasing automation.

There is an effort in these pages to break new ground on the fundamentals of innovation systems and the economic and technology development factors behind them, presenting a clear framework to approach science and technology policymaking.

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More specifically, the book explores the following innovation policy areas:

- The drivers behind science and technology support, including economic growth theory, direct and indirect innovation factors, Kondratiev innovation waves, innovation systems theory, the so-called valley of death between research and late-stage development, and public-private partnership models
- The organizing framework behind US science agencies, their missions and research organizational models, and the alternative Defense Advanced Research Projects Agency (DARPA) model
- The organization of innovation at both the institutional and personal, face-to-face levels
- Challenges in the energy, computing, and health innovation systems, as well as within legacy economic sectors in general
- The competitiveness challenge in advanced production technologies, including global innovation models
- Key issues in the science and engineering (S&E) talent base and workforce education system and pending employment and productivity issues
- Emerging efforts toward a functional industrial policy, featuring a federal role not only in R&D but also at other stages of innovation

Can science and technology policies play a vital role in meeting these complex challenges? Yes, they are full of promises—but promises that can be kept only if we organize these policies in new ways around these challenges. The chapters ahead are a road map for this project.

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1 ECONOMIC GROWTH THEORY AND DIRECT INNOVATION FACTORS

Physics remade the world in the 1940s. The immense and enduring flash of light from the Trinity atomic test in the New Mexico desert forced many people to revise their worldviews. One of the fields that it helped remake was economics.

If you asked any ten economists to explain a particular economic phenomenon in the previous decade, you would receive at least that many answers. The rigorous focus of physics on finding single, scientifically verifiable answers, as well as the field's unearthly glow, inevitably affected a new school of reforming economists who were determined to bring scientific discipline to their social science. Just as the physicists had isolated phenomena, they began to isolate basic economic phenomena and apply to each one a rigorous mathematical model. This postwar school of neoclassical economics aimed to replace prewar economics with systemic, data-based analytics.

One phenomenon that prewar economics never effectively confronted was economic growth. Apparent economic growth is a comparatively modern phenomenon. Think about medieval Europe. It was largely devoid of economic growth: economies were fixed for centuries; agriculture dominated, based on techniques that rarely varied; commercial sectors were minimal; and societies and their class structures were terrifyingly stable from generation to generation. To the extent that there was growth, it was largely achieved by piracy and conquest. European colonialization was a logical extension, in a way, of this wealth-through-looting framework.

The industrialization that began in the latter part of the eighteenth century marked a clear change. New economic pursuits and organizations bloomed, and growth became wildly apparent. Consider the nineteenth-century stories of steam engines, transcontinental railroads, and steel mills—with so-called robber barons finding new ways to capture wealth.

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Growth can be defined as the increase in the production of the quantity and quality of goods and services that support a population over time. Classical and then prewar economics had discovered two great tools for economic growth—labor supply and capital supply—and tended to see the economic world largely through those lenses. But it was a limited perspective.

ENTER ROBERT SOLOW

In the 1950s, Robert Solow, one of a number of postwar neoclassical economists who remade the profession, began his work ensconced in a perfect academic institution from which to observe technology and economic growth—the Massachusetts Institute of Technology (MIT).[1] Solow, like other postwar neoclassical economists, was committed to bringing mathematical discipline to his field. He looked hard at the work of two earlier economists, Roy Harrod and Evsey Domar, who had asked the crucial economic question at the heart of societal well-being: When is an economy capable of steady growth?[2]

Classical economists such as Adam Smith and David Ricardo had considered this question. But Harrod and Domar refined it, arguing in essence, in articles in 1939 and 1946, that an economy achieves steady growth when capital supply and labor supply are in the right balance. (Their growth model came to be called "modern growth theory" or "post-Keynesian," terms in widespread use among economists.) Put more exactly, they argued that growth occurred when the national savings rate (i.e., the income that a society saves) equals the capital output ratio and the rate of labor force growth. A society had to strive to keep its capital—plant, equipment, intellectual property, and financial assets—in balance with its labor supply. It could expand capital supply when it achieved solid levels of national savings, but these would be undone when counteracted by a labor supply imbalance—the labor force, not the capital plant, would receive too much of the national savings investment.

As Solow saw it, the Harrod–Domar world was a static one. There were only two major forces, labor supply and capital supply, with the savings rate serving as a variable that could be applied to either. Society struggled, like a drunk with wild mood swings, to maintain the correct ratios between the two. It was a Newtonian world in which forces varied but sought equilibrium. Solow felt that this presented a grim view of capitalism, one that vacillated between alternating periods of worsening unemployment and labor shortages, capital expansion and decline—a business cycle of relentless ups and downs. Solow had different instincts about capitalism. He decided that "the story told by these models felt wrong."

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Solow found that Harrod's work held a hint of what he felt was actually going on in Harrod's vague generalizations about entrepreneurial behavior. The classical formula for doubling a society's rate of growth was simply to double the national savings rate and then cope with the imbalance between labor and capital supply. Economic development theorists looking at the developing world in the postwar period kept returning to the classical model of growth. As Solow described it, under the prewar model, the "key to transition from slow growth to fast growth was sustained growth in the savings rate." Unsatisfied with that model, he said, "I thought about replacing the capital and labor output . . . with a richer and more realistic representation of technology."

Solow was seeking a new theory of production to replace the more static classical and prewar approaches. For economists, he was onto something breathtaking—what to him (and to us) seems so obvious was like discovering a new continent to economists schooled in a different worldview. He decided that the "old growth theory was mechanical"—it was simply "a description of flows and stocks of goods"—and the rate of growth is independent of the savings/investment rate. He found that "technological flexibility . . . opened up growth theory to a wider variety of real world facts." In other words, he had come up with a dynamic model of growth to supplant the mechanical one.[3]

By 1957, Solow's growth theory was spelled out. His research into historical economic trends showed three underlying developments. First, "gross output per hour of work in the US economy doubled between 1909 and 1949"—a dramatic productivity gain. Next, he found that "some seven-eighths of that increase could be attributed to" what he described as "technical change in the broadest sense." Third, his data showed that all the remaining 1/8 could be attributed to conventional increase in capital intensity." For 200 years, the economics profession had lived without a workable theory of economic growth. Then Robert Solow came along and announced in 1957 that the profession had somehow missed the monster in the room, "technical change in the broadest sense," and that this monster had to be accounted for.

Solow's breakthrough work led other economists to unpack his thinking. For example, as Solow has noted, Edward Denison undertook a detailed review of US economic growth from 1929 to 1982 to delineate Solow's term "technical progress."[4] He argued that growth in that period could be allocated in a highly precise mix: increased labor output, 25 percent; increased education qualification of the average worker, 16 percent; growth of capital, 12 percent (the same number as Solow found); improved allocation of resources (e.g., the shift of labor from agriculture to high-productivity industry), 11 percent; economies of scale, 11 percent; and growth of knowledge or technical progress (under Denison's more narrow definition), 34 percent. Although this totals

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109 percent, Denison found that the extra 9 percent is offset by miscellaneous factors that reduce growth.

When some of Denison's factors are lumped together to embody Solow's more sweeping description of "technical progress," his work bears out Solow's findings. Solow reduces growth factors to three broad ones: "straight labor," "straight capital," and "technical change." He argued that technology and related innovation—not just technology alone, but the bundle of things around it—account for up to two-thirds of US economic growth. Solow's fundamental finding is that "technology remains the dominant engine of growth."

To summarize, Solow attacked classical economics and transformed growth theory. He sees capitalism and growth as dynamic, rather than mechanical and static. If we think about it, we intuitively know that what he is saying seems right. The growth of the American economy has been transformed by a long sequence of technology breakthroughs: canals, railroads, the telegraph, electricity, the telephone, aerospace, computing, and its greatest application, the internet. We also intuitively know the pattern of transformation: an initial technology advance emerges; it yields new applications, which broaden the advance as they are adopted and yield major productivity gains (producing more with less labor input) throughout the economy. That, in turn, produces real economic gains and corresponding growth in real wages and income. This pattern occurs in a long wave of growth, which eventually peters out when the new applications stall and the economy-wide productivity gains from the innovative technology are achieved.

We have just been living through one of these big innovation waves, computing and its internet applications, and we have seen how that transformed the comparatively stagnant US growth rate of the 1970s and 1980s into the high growth of the 1990s. In the language of the times, it was "the next big thing."

As we think about it, Solow's basic point about old growth theory under prewar economics rings true: "No amount of statistical evidence will make a statement invulnerable to common sense."

The emergence of economic growth theory carries profoundly good news to economies around the world and the people who depend on them. Economics is not necessarily "the dismal science." You no longer have to be stuck in a static economic world. Your growth rate is not locked into the mechanical factors of capital and labor supply, which run in out of balance in worsening cycles of labor and capital undersupply and oversupply. Instead, capitalism turns out to be what we always knew it was—dynamic. You can act to improve your growth rate—your society or region can get better, create real growth in wages and income, and attain greater economic well-being. All you have to do is achieve Robert Solow's "technological and related innovation."

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Then, of course, comes the hard question: How are you going to achieve that? That's the challenge that this book addresses.

We should add to this overall positive story a distinction that later economists made between "embodied" and "disembodied" technological change.[5] Disembodied technology advances from research and development (R&D) projects—new technology products—that tend to improve employment in both upstream and downstream sectors. But implementing advances in embodied technologies—which improve processes and production to enhance productivity—can result in employment shifts and declines, as well as overall productivity gains.

Let's explore a little more, too, the role of capital investment under Solow's growth theory. Clearly, it plays a supporting role. Solow found that "technological progress . . . could find its way into actual production only with the use of new and different capital equipment." Therefore, "the effectiveness of innovation in increasing output would be paced by the rate of gross investment." Solow saw that technological innovation does not occur in a void—you can speed the transfer of new technology into production with capital investment. But in the end, investment itself cannot create the advance; the investment is the servant of the technological advance.

Of course, this raises the question of what kind of capital investment best serves technological advances. We now have a multitude of choices—angel, venture capital (VC), initial public offerings, equity, lending, or a mix of all of these. Solow doesn't speculate on this topic, but we will examine a number of these financing options in later chapters.

Another point about Solow: he doesn't pretend that boom-bust cycles are over. He notes that periods of boom and stagnation do appear, recognizing Keynesian (unemployment in a downturn is a normal state without governmental intervention) and classical (economies tend to return to full employment) unemployment theory. The point that he raises is that you can reduce the stagnation periods by accelerating the rate of technological innovation. By implication, he may be suggesting an idea that we will consider further: robust innovation capacity is critical to stagnation cycle reduction.

Solow's growth theory is exogenous. In other words, economic growth evolves because of influences outside the models that neoclassical economics tracks as making up the economy. This underlying assumption is that economic prosperity is primarily determined by external, independent factors, as opposed to internal, interdependent factors. These exogenous factors are those that surround technological advances: technology development and its supporting infrastructure, from management to production, that implement the advances. If it is not economically interdependent, then it is hard for economics to measure. Solow came up with the key element behind 60 percent or more of economic growth, but he found it was outside the neoclassical economic system.

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Solow won the 1987 Nobel Prize in Economics for his growth theory, three decades after he first offered it. For the advance in thinking about the role of technology that he spurred, he was awarded the President's National Medal of Science in 1999.

At MIT, Solow had a rich reputation not only for his brilliance but for being approachable and thoughtful. I once accompanied him to a congressional science and technology subcommittee hearing in Washington at which, after some opening remarks by committee members and witness testimony, Judy Biggert, a Republican congresswoman from Illinois, called him a hero for his work underscoring the importance of technology advances to economic progress. Solow responded that he had been a tech sergeant in the US Army during World War II and that he'd rather be called "Sarge" than "hero."[6]

It was a charming, funny, self-effacing moment in what had been a staid hearing. From then on, the committee was eating out of his hand, with members calling him "Sarge" and carefully considering every point he made.

Solow had the virtue of seeing his economics in perspective. Interestingly, he closed his Nobel Address with a warning about the importance of his growth thesis. Quoting the American poet Robert Frost's "Black Cottage," he said, "Most of the change we think we see in life is due to truths being in and out of favor."[7] He also placed his economic work in historical context: "Social institutions and social norms evolve . . . so economic behavior will surely evolve with them." He was suggesting that his growth theory captured the technological emphasis of late twentieth-century developed nations, and this model could change with time. He closed his address by bluntly putting economics in its place: "The permanent substructure of applicable economics cannot be so very large."

This was quite a statement from a leading neoclassical economist. If neoclassical economists such as Solow were trying to turn economics into a physics-like science, why was he acknowledging that growth theory and economics in general had only transitory historical permanence and would have to be remade in a different societal context? Arguably, Solow had no choice because growth theory itself drives its proponents to that conclusion.

Growth theory, with its emphasis on technology and its evolution, has to look closely at history. If innovation occurs in a complex system of interacting factors, and many of these factors are soft and not prone to mathematical summary, other social sciences have to play an analytical role. If a society's innovation capacity is key to its technology evolution, and therefore its growth, the organization and culture of that society have to be understood.

As Solow's Nobel Address recognized, in a way, the growth theory that he first enunciated plants land mines around the well-ordered, mathematical world of neoclassical economics. And those land mines have started going off. This book will try to look at

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innovation as a complex system and build on Solow's work to try to rope in some of these variables and put them into the beginnings of an analytical framework.

ENTER PAUL ROMER

Paul Romer is the second of the great economic growth theorists whose work we will explore (we will look at his role as an education critic in chapter 11).

My favorite photograph of Romer shows him leaning against a column at Stanford University, the fingers but not thumbs of his hands in the two front pockets of his faded blue jeans, a rumpled tweed jacket open and thrown loosely back at his sides, and a dark T-shirt poking out from under a partially buttoned white pullover. He looks so relaxed, the very image of tanned and fit good health, just leaning there, with a full head of longish dark hair and a big, wide California smile. He just looks so, well, California.

One very likeable aspect about Romer is that he is a maverick, and it's rare for mavericks to win recognition in the economics community. He took four years off from teaching economics at Stanford's business school because he found it to be a thoroughly inefficient way to convey its core ideas to economics students, and he set out to invent a new way of teaching. He developed a new kind of interactive textbook based on problem sets that made all other economics textbooks obsolete—to the chagrin (and economic loss) of other economics textbook authors, who then had to follow his approach.

In a 2016 speech, Romer declared, "For more than three decades, Macroeconomics has gone backwards."[8] He has castigated fellow economists for the damage that their doctrines have done, arguing that they share the blame for lowering life expectancy, the opioid crisis, and subprime lending.[9] He resigned from his position as chief economist at the World Bank after attacking its economists for the way that they developed data.[10] He is one of the few economists who have dared to say some of these things out loud.

His focus is on the talent that stands behind the technological innovation that Solow emphasized. His 1990 article "Endogenous Technological Change" was a breakthrough in economic growth theory.[11] It was largely this work for which he won the 2018 Nobel Prize in Economics, and in which he made a series of basic points summarized next and then explored in greater detail later in this book.

Romer's growth model is Solow's—growth is driven by technological advance—but with added dimensions.[12] He argues that it is the stock of human capital, *talent*, that determines the rate of growth, playing a central role. In societies in general, however, too little of this human capital is devoted to research, he says. And since research is the major input into technology, talent—he refers to it as human capital employed in research—is very much a driver of growth.

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There is another element to Romer's work: he wants to put the genie of growth back into the economics bottle. He rejects Solow's view that growth theory is exogenous, arguing instead that it is endogenous.[13] After all, we might ask, what good is economics if the core theory of economic growth is exogenous and outside it?

Romer's growth model notes that output per hour of work (productivity) by 1990 was ten times as valuable per hour worked as it was in 1890. In his view (similar to Solow's), the cause is technological innovation. He then asks the next logical question: What other factors generate the growth of output per worker? His answer is that they are the increase in the effective workforce and the increases in effective stock of capital per worker. He has three premises.

First, as noted previously, technological change lies at the heart of economic growth. Romer defines technological change as an "improvement in the directions for mixing together raw materials."[14] Perhaps because this was written in 1990, before the widespread advent of software and a mixed services–information technology (IT) sector, he saw technology as a physical product, not a process. While his definition may need expanding,[15] his underlying point about technology-based growth remains. He further suggests that technology provides the incentive for capital investment and capital accumulation, not the other way around. This combination of technology and capital is what leads to the improved output per worker of products—the productivity gain that enables real income gain in the economy.

His second premise is that technological change occurs largely because of people—let's call them "technology change agents"—who respond to market incentives. He acknowledges that academic scientists working on government research grants may not do so, but when their knowledge begins to be translated into practical goods, market incentives are key. Technological change drives growth and in turn is driven by researchers—who are what Romer would call "profit-maximizing agents" operating at the immediate precommercial stage.

His third premise is that technological knowledge (again, in his terms, "instructions for working with raw materials") is inherently different from other economic models. This technological knowledge, the process of developing new and better "instructions," operates as a fixed cost and is not inherently profitable in itself.[16]

Romer's exploration of technological knowledge is an important part of his exposition, so it is useful to review his underlying definitions. He defines a "nonrival good" as property that, if used by a person or firm, in no way limits its use by another. So the nature of technological knowledge is nonrival, and it can be readily shared or adopted by others. It can also be made "excludable"; that is, property ownership of technological knowledge can be established through legal patents or commercial treatment as trade

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secrets, which prevents others from using it. Since so much science is in the public domain, however, technological knowledge can only be "partially excludable." Thus, technological knowledge has both nonrival and excludable attributes. If it were entirely nonrival, there could, in theory, be "unbounded growth," but economic incentives crucial for his second premise would be missing. Therefore, aspects can be excludable, but excludability is incomplete, and appropriation is only partial.[17]

For Romer, then, technology is not a private good, nor is it a public good—it is a nonrival, potentially excludable good. It won't support price-taking competition, so it's more like monopolistic competition. Technological knowledge thus has unique property features.

There is an unsettling further conclusion to be drawn from Romer's portrayal. To the extent that an economy is based on superior technological knowledge, and because this factor, in Romer's terms, is inherently nonrival and only partially excludable, technological leadership can be appropriated and transferred—you can exercise only an imperfect monopoly over it. Inevitably, it spills over into many hands.

In both the second and third premises, Romer is announcing an endogenous theory of growth driven not simply by new technologies themselves, but also paced by "human capital employed in research."[18] This technological knowledge becomes key, and as noted, he finds that it is driven by market incentives. And this technological knowledge can be characterized as a good, but it is a different kind of property, one with economic characteristics such as "nonrival" and "excludable." With this analysis, he is attempting to bring economic ideas into his concepts of technological talent and the technological knowledge to which it leads. He is parting ways with Solow and exogenous growth theory.

Not content with announcing a new aspect of growth theory, Romer also suggests a new theory of civilization. He argues that an increase in the total stock of human capital engaged in research and a corresponding increase in the amount of research are directly proportional to the increase in economic growth. If human capital engaged in research is too small, economic stagnation results. This, he suggests, was the prehistoric condition. Growth, and therefore civilization, could not begin until human capital could be spared from production and consumption and allocated to research.

Romer notes that the total level of human capital and the proportion of that capital devoted to research by the time of his 1990 article were at the highest level in history. Yet given the power of technology for growth, he argues that our investment in human capital/research remains far too low. He criticizes government policies that aim to spur growth through capital subsidies such as capital gains tax cuts or tax cuts in general. These approaches are misplaced and inefficient. A government's best policy to spur

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growth would be to use subsidies and incentives to increase the allocation of human capital to research. Failing this, the next best solution would be to subsidize the production of human capital trained to engage in research.

Romer also has interesting things to say about the relationship between growth, trade, and research.[19] A large population is not enough to generate growth; the key is the quantity of human capital engaged in research. He notes that growth also appears to relate to the degree of integration into world markets. Having a large number of consumers or a large population is not critical and is no substitute for trade with other nations. The key is integration with large supplies of human capital, and trade enables that integration. An economy with a large stock of human capital engaged in research fosters growth, then, with trade as an additional enabler. This accounts for the unprecedented growth of twentieth-century economies. Less-developed economies can benefit from access to human capital through trade and the integration that it brings. This, Romer believes, is the underlying story of the growth of Asian economies. Closed economies that cut themselves off from this talent and technological knowledge stagnate.

In summary, Romer makes a great contribution by fleshing out a key feature behind the story that Solow uncovered. Solow identifies "technological and related innovation" as the largest and critical factor behind economic growth; Romer looks at what lies behind that factor. He finds that "human capital employed in research"—talent—is the key input, and that means that you can't just train scientists and engineers, but they must be put to work, engaged in technological research and advancement.

Romer's rich thesis that technological change comes from researchers (and follow-on entrepreneurs) responding to economic incentives is often referred to as the "prospector theory." Let's look at the emergence of strong chemical industries in late nineteenth-century Europe. Two countries dominated this industry, Germany and Britain, and the critical characteristic that they both shared was the training of large numbers of talented chemical engineers and scientists.

Compare this to the 1849 gold rush in California, where an immense fortune in gold was found once a hoard of prospectors arrived. If one nation fielded a small number of well-trained prospectors and sent them off to the gold fields, and another nation fielded a vast armada of well-trained prospectors, which nation would find more gold? From Romer's perspective, what Germany and Britain did in the nineteenth century in the chemical field was, in essence, send out great numbers of prospectors, and both nations' researchers discovered an astounding amount of chemical gold. They also created major industries that dominated a new part of the world economy, significantly improving their economic growth rates.

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Romer's prospector theory is both simple and profound. It does not contend that the largest number of prospectors find the technological gold, but rather that the largest number of *well-trained* prospectors find the most technological gold. The theory also makes a simple assumption about technical knowledge as being like a goldfield, just sitting there waiting to be uncovered and mined. That also seems intuitively to be right: there's a vast goldfield of knowledge waiting to be found by the right army of seekers. This simple observation is also a profound policy assumption.

Romer's connection of talent to technological innovation provides us with the second key factor to understand economic growth.

LOOKING AT THE 1990S: DOES SOLOW'S AND ROMER'S WORK HOLD UP?

Let's test what Solow and Romer contend regarding a deep relationship between innovation and economic growth against the history of the 1990s and that decade's technology breakthroughs.

The Harvard economist Dale W. Jorgenson performed a detailed survey of the 1995–2000 period and found that the resurgence of the US economy at the time outran all expectations and projections of traditional economics.[20] Jorgenson was an expert on "total factor productivity," the ratio in economics of aggregate output to aggregate input, particularly labor and capital, with the difference accounting for the role of technology advances. So a study of semiconductors was right in his wheelhouse. He identified the sharp decline in IT prices as a key enabler for this 1990s surge in US economic growth, arguing that this development is rooted in the semiconductor technology sector.

Like most technology enablers, the semiconductor had a decades-long gestation period. The story dates to 1947, when AT&T, facing increasing competition in the electronics sector from the huge advances undertaken by many researchers and companies on behalf of the US government during World War II, assembled a remarkable team of researchers at Bell Labs under John Bardeen, Walter Brattain, and William Shockley (there will be more to say about this remarkable team of first-generation, solid-state semiconductor physicists in chapter 5). Developing semiconductor theory, they built, in a "magic month" from November to December 1947, the first transistor—an electrical switch for encoding information into binary (or digital) form.

Jack Kilby at Texas Instruments and Robert Noyce of Fairchild Semiconductor led the next critical stage of advancement. They developed the integrated circuit (IC)—a network of semiconductor-based transistors that eventually enabled millions and millions of networked semiconductor transistors to store data in binary/digital form. The

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first ICs were for memory storage—memory chips or dynamic random access memory (DRAM).

Gordon Moore of Fairchild Semiconductor saw that evolution and proclaimed "Moore's Law": new ICs every two years will double the number of transistors per semiconductor chip, and the cost per transistor will be cut in half in the same period. This introduced a dramatic deflationary factor into the world economy: ever-greater performance at ever-lower cost.

In 1968, ten years after the IC was introduced, Noyce, Moore, and Andy Grove teamed up to create Intel and begin making semiconductor microprocessors (or logic chips or microchips), which move beyond memory storage to logic processing on a chip. The first Intel microprocessor had 2,300 transistors; by the year 2000, an Intel Pentium 4 had 42 million transistors. (While it's outside the 1990s, by 2021 IBM had announced a density of 330 million transistors per square millimeter, at a 2-nanometer scale, on a chip.)

Let's look at what the numbers tell us.[21] In 1978, the price of a transistor on an Intel 8086 microprocessor chip was 1.2 cents; that chip held 29,000 transistors. Following the relentless logic of advance under Moore's Law, the price of a transistor on Intel's Itanium 2 microprocessor chip was 0.000002 cents by 2003; that chip held 410 million transistors. At this rate, chip capability doubled every 1.6 years, with the price per transistor falling in half each comparable period. Moore's Law ruled in the 1990s. (Physics says that what you can fit on a chip eventually reaches a limit because you run out of atomic scale. So Moore's Law began to break down in the 2010s. A race is now underway to pursue—by other means—more power, more speed, and less energy per chip.)

Jorgenson noted that while Moore's Law was running, this deflation in semiconductor prices drove down the costs of the computing technologies that they enabled. This tracks with the data. The cost of 1 million instructions per second (MIPS) for a 1978 Intel 8086 microprocessor was $480, and the cost per MIPS for a 2003 Intel Itanium 2 microprocessor was $2. Thus, the dramatic advance in semiconductor capability, truly exponential growth, has enabled significant, if not quite as dramatic, advances across all the critical computing components: memory, processors, storage, sensors, and displays. Computing power has grown 100 times per unit cost over the past half century. By 2004, not long after the explosive 1990s IT decade that we're examining, Robert Atkinson noted:

> The average U.S. household contains more computer power than existed in the world before 1965. Smart cards (plastic cards with an embedded computer chip in them) have more computer memory than the first Commodore computers. A Palm Pilot has more computing power than the IBM 3083 mainframe computer of the early 1980s, while a new personal computer (PC) has 250 times more power than IBM's first PC, introduced in 1981. IBM's new "Blue Gene"

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> supercomputer can make 360 trillion calculations per second, compared to around 2 billion calculations per second in the late 1980s for a typical supercomputer.[22]

Jorgenson noted that communications equipment costs—for transmission technologies including fiber optics, microwave broadcasting, communications satellites, and dense wavelength division multiplexing (DWDM), which are multiple simultaneous signals over fiber-optic lines—were similarly driven down by semiconductors during that 1990s period and were crucial to the so-called free internet.[23] The accelerating growth in output led by all these technologies encouraged a corresponding boom in productivity in the 1990s. Price declines characterize all these technologies, with computers experiencing a 15 percent decline per year between 1990 and 1995 and a 32 percent decline per year between 1995 and 2000, allowing rapid acquisition of these productivity-improving technologies. All these multiplier effects, led by semiconductors, a critical enabling technology, helped build the US growth resurgence in the 1990s.

The productivity gains in that period were particularly crucial because they enabled real economic gains throughout the economy. From 1945 to 1973, annual US productivity growth was around 2 percent. From 1973 to 1993, it fell into the 1 percent range, and then from 1995 to 2000, it went to 3.5 percent or higher, with the US growth rate reaching 4.2 percent. This was a very dramatic shift.

Jorgenson argues that the massive increases in computing power in the US initially raised productivity rates in IT-producing industries and then contributed to productivity increases in the broader US economy. The IT sector as a whole increased productivity steadily from 1948 to 1995 and then accelerated sharply in response to semiconductor price drops from 1995 to 2000. But this was not an isolated phenomenon. The purchase of productivity-enhancing IT equipment throughout the economy drove the US growth rate up one full percentage point in this period, and the advances in the IT sector alone accounted for half of that. Thus, although the IT sector alone accounted for only around 5 percent of US gross domestic product (GDP), it yielded the 1990s surge in productivity and, therefore, economic growth. Here's the pattern: IT advances drove capital investment into IT-based capital goods, which were widely adopted in many sectors; this, in turn, drove productivity gains throughout the economy, which drove US economic growth in the 1990s. Jorgenson's analysis of the 1990s economic surge puts flesh on the skeletal theory of economic growth pioneers like Solow and Romer.

To summarize what happened: First, a technology invention, the semiconductor-based transistor, became incorporated into an innovation through the widespread use of the semiconductor as an enabling technology for computing and communications. Many new applications were then piled onto these breakthroughs, from the mainframe to the desktop to the internet to fiber-optic infrastructure, to build an entire IT sector,

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which in turn reached into other sectors. That produced dramatic productivity savings throughout the economy and a dramatic burst of economic growth.

The 1990s story vividly illustrates Solow's thesis of "technological and related innovation" as the leading force behind the economic growth of that period. The role of talent, through such figures as Bardeen, Kilby, Noyce, Moore, Grove, and many others, was crucial at each stage of technology advancement, supporting Romer's emphasis on talent as the key technological innovation enabler. The 1990s period of high productivity and growth clearly demonstrates Solow's and Romer's growth theories at work.

DO INVESTORS SEE THINGS THIS WAY?

It's one thing if a particular school of economics, growth economics, sees a relationship between technological innovation, talent, and growth. It's a bigger thing if investors see the same linkages. Why is it bigger? If, as Solow argues, investment is only a handmaiden to technology development, it is nevertheless necessary for a robust innovation system.

How do investors look at potential technology breakthroughs? Do they believe they drive growth?

Here's how investors, as the 1990s ended, reacted to what they had been seeing. In 2001, just as the stock market's dot-com bubble was bursting, Merrill Lynch, one of the nation's largest brokerage houses, published a report for its clients titled "The Next Small Thing: An Introduction to Nanotechnology."[24] Prepared by two of the firm's leading economic analysts, it provides a good picture of how a leading market investment firm thought about innovation.

Citing the senior Merrill economist Norman Piore, the report boldly asserted growth theory, that innovations drive the economy and the stock market. Piore argued that it takes approximately 28 years for wide acceptance of a new technology, 56 years for rapid growth to evolve, and 112 to reach technology maturity. After that, growth in an innovation technology area will simply parallel the rate of population growth. While the report does not spell out how Piore derived these numbers, the first two timelines seem roughly accurate for the timetable of the semiconductor-computing-IT revolution that we have just been examining. It would be nice if Merrill's century-plus estimate for technology maturity is accurate—it would take until around 2080 for the IT revolution to run down.

The Merrill report proceeded to argue that these timelines are now well underway for nanotechnology, the capability to fabricate at the molecular scale (i.e., at 100 nanometers or less, where a nanometer equals ten hydrogen atoms). It described three evolutionary stages that nanotechnology had already completed. The first is the *vision* stage, and the report suggested that the physicist Richard Feynman set forth the basic vision in his

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famous 1959 lecture "There's Plenty of Room at the Bottom."[25] Then comes the *enabler* stage, where enabling technologies and tools develop. This stage began with IBM's development of the scanning tunneling microscope, which allowed observation and manipulation of atoms. Finally, achieving *research mass* is the third stage. Eric Drexler of MIT launched this stage in a well-known 1981 journal article on nano possibilities.[26] By 2000, the Merrill report noted that the number of journal articles mentioning nanotechnology published that year reached 1,800, similar to the total number of journal articles mentioning the internet in the early 1990s.

The report noted that although there were fascinating "futuristic" applications of nanotechnology, achievement of those future markets was "not inevitable," and hence they were not good investment risks.[27] However, there were aspects of nanotechnology that were "close to commercial markets," and the report reviewed a series of nanotechnologies with "short-term," and therefore investment, potential—with "short-term" defined as no more than two years from the appearance of the actual product, "midterm" as two to five years, and "long-term" as five or more years. Merrill's summary provided a good perspective on how far investors would need to look for investment opportunities.

There is a deep irony here. Although Merrill defined the lengthy timeline for widespread acceptance of a new technology, it was only ready to support short-term investments of less than two years.

The report also found that "the keys to nanotechnology" are manufacturing and communication. "If you can't build it in volume, then there's not much you can do with it," the authors wrote.[28] It went on to focus on investment opportunities for the zero-to two-year, short-term period. Asserting that "in any new technology the first winners are the tool makers," it argued that there are early investment opportunities in instrumentation technologies as nano enablers, emphasizing that interdisciplinary work will be key in this area to "accelerate research and commercial spin-offs."[29]

A second area that Merrill examined is semiconductors; the report quotes Hewlett-Packard's leading researcher, Stan Williams: "Within the next ten years molecular electronics is expected to become available as a replacement for silicon-based computing."[30] In retrospect, since semiconductors as of 2022 are being fabricated at the 5-nanometer scale and headed lower, we can see that Williams was absolutely right, although silicon is still with us. But that was too long a timetable for investor interest, so Merrill suggested that investors hold off on nano-microprocessors. The report suggested that an interim step then being researched by Intel's Gary Marcyk to make merged silicon and nano "complementary microprocessors" as a transitional phase in the midterm could prove a safer option.

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Merrill's report provided both good and bad news. It showed that practical investors see the economy as driven by technological innovation and support driving investment into relevant fields for growth opportunity. It presented a thoughtful review of the phases required for new technology advances. But it is also a cautionary tale. Merrill was interested only in new technologies no more than two years from actual production and market entry as new products. Since the Merrill report told us that it takes twenty-eight years, on average, for a new technology to move through R&D stages toward "wide acceptance," and Merrill was telling its investors to support only the last two years of that process, who is going to support the other twenty-six years of technology R&D?

If Solow is right, as the Merrill report implicitly argued, and "technological and related innovation" is key to economic growth, then that twenty-six-year hole is a big problem for his model. Similarly, if Romer is correct that talent availability is key to such innovation, as the Merrill report's frequent cites to leading researchers implicitly supported, then who is going to support the talent pool during that twenty-six-year hole before private investors step in?

The answer to this hole that our economy has frequently stumbled into has been a largely unconscious policy to treat that gap as a public good, during which the government provides major support for both R&D and talent.

DIRECT INNOVATION FACTOR 1: R&D INVESTMENT

One basic point that has emerged from this discussion so far is that if Solow is right, and "technological and related innovation" is responsible for half to two-thirds of historic US economic growth, then R&D investment is a critical pillar for our economy's well-being. We'll call this pillar a *direct innovation factor*. Since the Merrill report suggested that private-sector investors are prepared to support only the late stages of the innovation process (an issue explored in much more detail later in this book), the role of government R&D support becomes paramount for the early stages.

As an introduction to the problems that this book will more thoroughly explore, let's look at a series of snapshots of the health of the government's R&D portfolio.

The first snapshot (figure 1.1) shows federal R&D spending as a percentage of US GDP through 2021, as well a federal R&D as a percentage of federal outlays. Percentage of GDP may be the best measure of R&D investment because it shows the level of *societal* investment in R&D. Both hit record lows in 2021.[31]

The figure shows a rapid climb from 1950, where R&D spending began as below 0.5 percent of GDP, to a high-water mark around 1965, when it climbed over a full percentage point to just shy of 2 percent of GDP. Since then, it's been largely downhill, and

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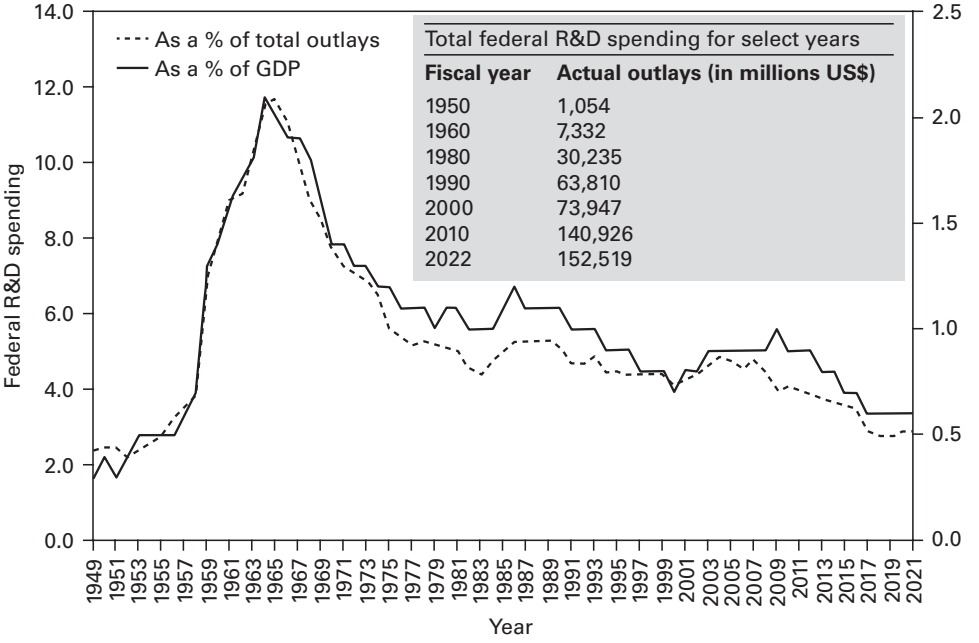

Total federal R&D spending for select years

Fiscal year	Actual outlays (in millions US$)
1950	1,054
1960	7,332
1980	30,235
1990	63,810
2000	73,947
2010	140,926
2022	152,519

FIGURE 1.1

Federal government R&D—government R&D outlays and government funding of R&D as a percentage of GDP.

Source: Data from the Office of Management and Budget (https://www.whitehouse.gov/omb/budget/historical-tables/) and American Association for the Advancement of Science (https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd).

as of the beginning of the 2020s, it seemed stuck where it started in 1950: well below 0.5 percent. While President Joe Biden's administration increased federal *development* spending in 2021–2022 (as discussed in chapter 12), it is unclear whether that can be sustained politically.

Why did we reach such a high level of federal R&D funding in 1965? Given the major role of defense support for R&D in the US, the answer is probably the US involvement in a hot war (in Vietnam), a cold war, and a space race to the Moon. While 1965 might not, therefore, be the ideal benchmark, given the importance to our growth of R&D of innovation and federal support for R&D, it doesn't seem smart to build a strong innovation-based economy on a declining rate of societal R&D investment. Federal support for research faces ongoing challenges, given the problematic long-term fiscal posture of federal government and the growing costs of social and medical benefit programs in future decades for an aging population.

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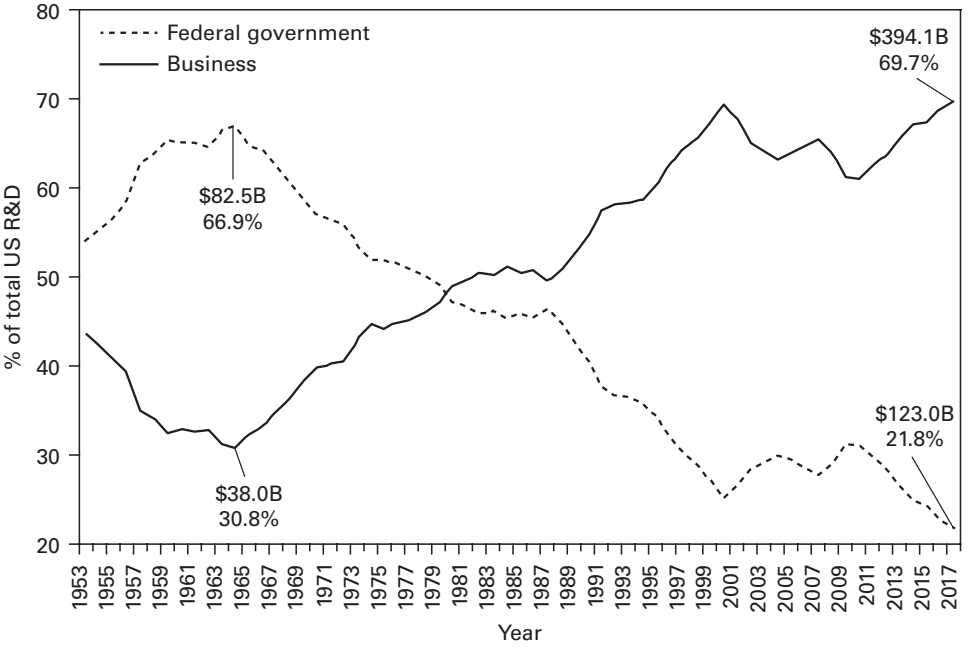

FIGURE 1.2
R&D funding from the federal government and business sector.
Source: Data from the National Science Foundation (NSF) (https://ncses.nsf.gov/pubs/nsf23320/figure/2; https://www.nsf.gov/statistics/2018/nsb20181/figures#chapter1038).

The second snapshot (figure 1.2) shows business-sector R&D investment superimposed on the curve of federal R&D investment from 1953 to 2018 (in 2019 dollars).

On its face, this chart looks like great news. Even though federal R&D as a percentage of total R&D is in steep decline, private-sector R&D spending is on a long-term rising curve. In fact, while public-sector R&D has declined from two-thirds of total US R&D in 1961 to below one-quarter in 2021, the private-sector role has risen from one-third to two-thirds of total US R&D. That *looks* terrific, like the private sector is picking up the public sector's slack. What a great outcome for capitalism!

Unfortunately, the story is a little more complicated.

As the Merrill report suggested, the public and private sectors play different roles in the R&D process. Overwhelmingly, the public sector tends to support the *research* part of R&D, supplying some 80 percent of it, while the private sector funds more than 90 percent of *development*. The good news is that the IT surge of the 1980s and 1990s apparently enticed the private sector to increase that role in R&D investment significantly (analyses

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of R&D sectors, in fact, show that this private-sector rise was largely in IT-related areas). The bad news remains that the government has been decreasing its level of research investment.

Arguably, a healthy R&D system would show not "X" curves of rising private-sector and declining public-sector R&D investment, but instead curves rising in parallel for both sectors. This "X"-curve snapshot may suggest an interesting evolving story, although it would take much more analysis to prove it. The hefty government R&D investments in the 1960s may have fueled the early-stage development of the IT revolution of the 1990s, given the typical thirty-year lead time for technology evolution. That, in turn, could have promoted the rising private-sector late-stage development investment in IT shown in the rising curve on the chart for private-sector R&D. However, the declining federal investments in *R* in recent years may reduce our innovation capacity in the future, and if new technology ideas don't keep emerging from federally supported research, this may lead to a parallel decline in private-sector late-stage *D* investment because the public sector hasn't adequately supplied the foundational research building blocks upon which the private sector builds.

This story assumes an interactive relationship between *R* and *D* and between public- and private-sector roles in innovation. It further assumes that there is an innovation system, of which R&D is a critical component. These ideas will be explored carefully as we go along.

One more point should be emphasized. Data on levels of R&D investment don't tell us about the quality of that R&D investment. It's not enough to invest in R&D. A society's public and private sectors must invest *wisely*.

The third snapshot (figure 1.3) shows federal funding for fundamental research by science and engineering (S&E) fields in inflation-adjusted dollars between 1953 and 2017. It reveals an increasingly imbalanced portfolio.

Overall, looking at the percentage share of federal R&D funding, there was a dramatic tilt: declines in the share of funding for physical sciences, engineering, mathematics, psychology, and computer science, but dramatic growth in the percentage share for life sciences.[32] The failure of the physical sciences to garner the support to keep pace is problematic. Many science experts now argue that a host of important future advances will come from interdisciplinary collaboration and the space between existing disciplines. For example, dramatic biotechnology advances have come from the combination of biology with computer science and other physical science–based fields. If life science advancement continues to outpace physical science advancement dramatically, the ability to ensure this interdisciplinary collaboration is potentially jeopardized, thus making life science advancement also a challenge, eventually.

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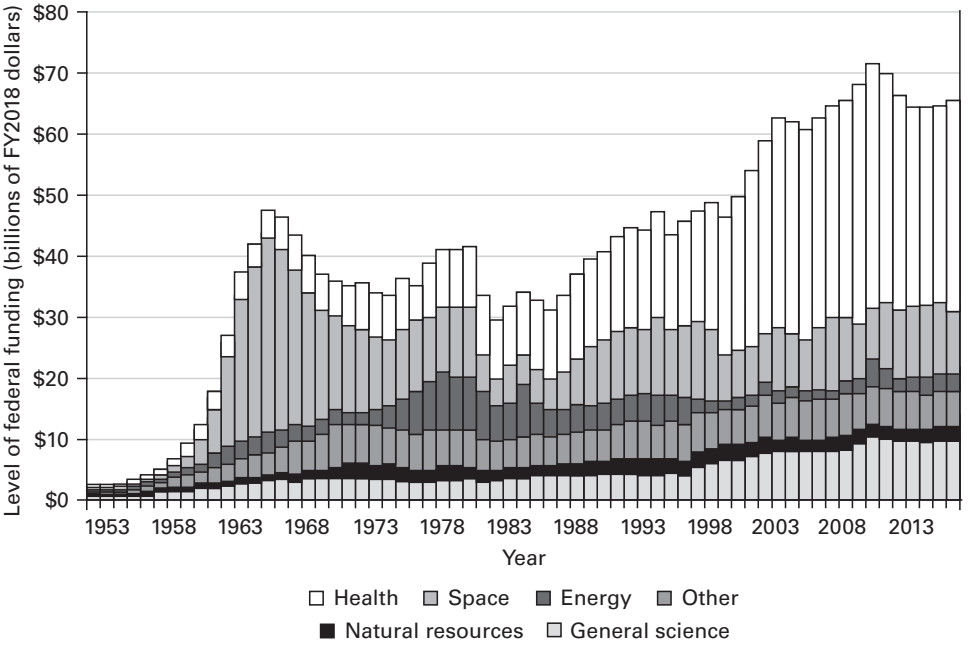

FIGURE 1.3
Federally funded nondefense R&D by science area.
Source: Data from the American Association for the Advancement of Science (https://www.aaas.org/sites/default/files/2019-01/AAAS%20R%26D%20Primer%202019.pdf).
Note: Some energy programs shifted to general science beginning in 1998.

While the US continues to lead global R&D, that margin is rapidly narrowing, and China will soon take the top position. Figure 1.4 shows R&D by country or region; note China's sharp rise.

Another underlying reality is the increasing globalization of R&D undertaken by industry—a process that has been long underway. R&D in the US by US affiliates of foreign firms, as well as R&D conducted abroad by foreign affiliates of US parent firms, has grown.[33] The formerly national system of innovation in the US has increasingly become globalized.

In summary, assuming that Solow is right about the connection between growth and technological innovation, and that innovation is connected to R&D investment, these snapshots show emerging patterns in US R&D spending that may prove problematic for its innovation capacity. Federally supported R&D, which supplies the great bulk of the research side of R&D, has been in a long-term decline as a percentage of GDP. Within that decline, there is one bright spot—federally funded life science research is

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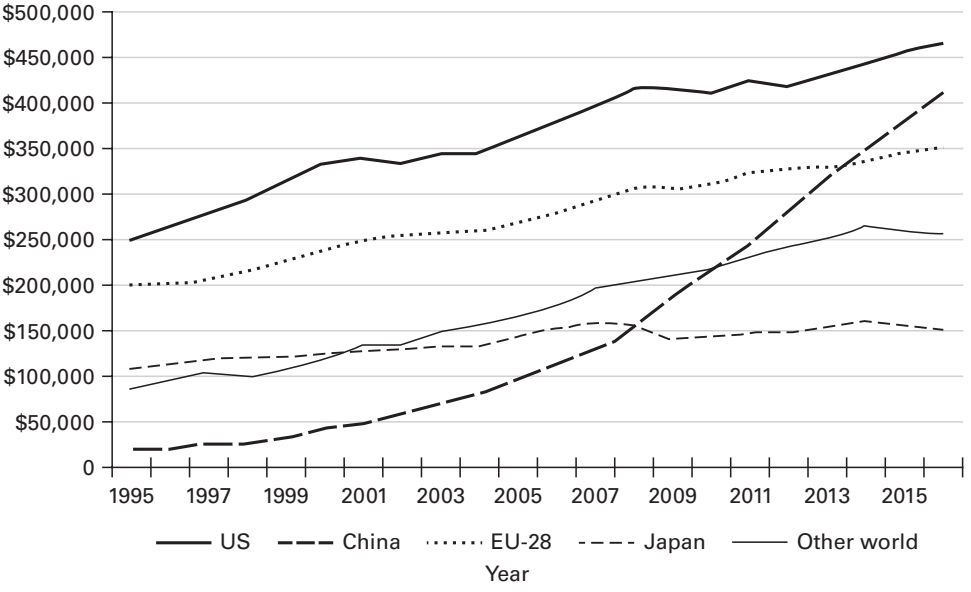

FIGURE 1.4
World R&D by country/region.
Source: Data from the American Association for the Advancement of Science (https://www.aaas.org/sites/default/files/2019-01/AAAS%20R%26D%20Primer%202019.pdf).

accelerating, having doubled between 1998 and 2003 and increasing again by the present day. However, given the overall pattern of federal research decline, this life science increase masks a significantly steeper decline in physical science research investment. On the industry side of R&D investment, which is overwhelmingly for *development*, this funding has been surging. However, this may be affected over time by the declining rate of federal research support, which serves as its foundation. In addition, US industrial R&D is increasingly globalizing, which may have implications for the strength of US national economic growth rates.

DIRECT INNOVATION FACTOR 2: TALENT

A second basic point has emerged from this discussion so far. If Romer is correct and "human capital employed in research"—"talent" in shorthand—is a critical input for a society's technological advancement, then talent is our second direct innovation factor.

Scientific talent in the US economy receives major funding from the federal government, both in the form of federal support for graduate science education and federally

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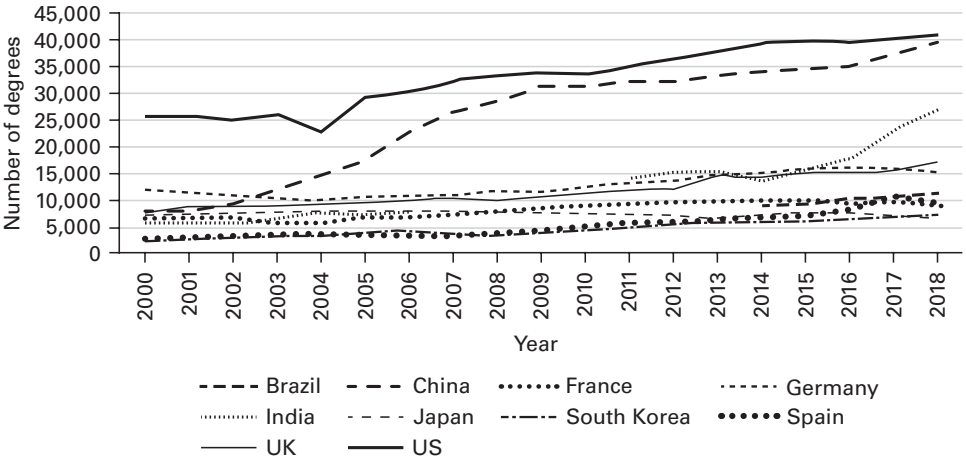

FIGURE 1.5

S&E doctoral degrees by selected countries, 2000–2018.

Source: Data from the NSF (https://ncses.nsf.gov/pubs/nsb20221/u-s-and-global-stem-education-and-labor-force), drawn from the Organization for Economic Cooperation and Development (OECD) (Europe); Ministry of Education, Culture, Sports, Science and Technology (Japan); National Bureau of Statistics and Ministry of Education (China); and Ministry of Human Resource Development (India).

Note: Data are not available for all nations for all years.

funded scientific academic research through which graduate students receive mentor-based research training. As an introduction to further discussion of science education in this book, let's examine a series of snapshots of US talent patterns.

The basic point of Romer's prospector theory is that the number of well-trained prospectors that a society or region fields will directly affect the extent of its scientific and technological discoveries. The talent base is a dynamic factor. You shouldn't try to constrain the size of your talent base to what you expect will be the size of your economy. Instead, Romer tells us that your talent base will be a key element of the size of your economy.

Given the dynamic role of the talent base, how do US talent numbers stack up? In total number of higher-education degrees in the US increased between 2000 and 2020. The number of all degrees at all levels (including associate degrees) increased from 561,000 in 2000 to 1,087,000 in 2020, with an increase in the percentage share of S&E degrees among all degrees from 24 to 27 percent.[34]

Figure 1.5 shows the changes in S&E doctoral degrees in selected countries between 2000 and 2018.

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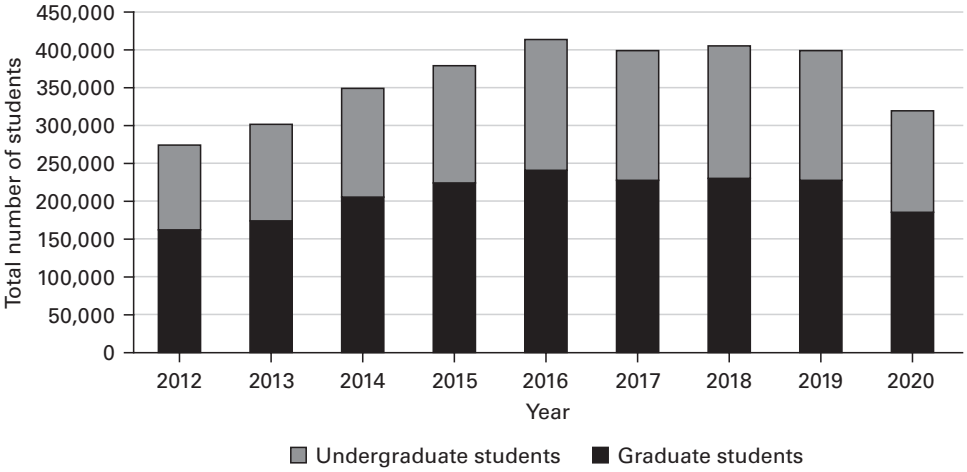

FIGURE 1.6
International students enrolled at US institutions of higher education by academic level, 2012–2020.
Source: Data from the NSF (https://ncses.nsf.gov/pubs/nsb20221/u-s-and-global-stem-education-and-labor-force), drawn from the US Department of Homeland Security, US Immigration and Customs Enforcement, and the Student and Exchange Visitor Program.
Note: Numbers are rounded to the nearest 10.

For decades, the US has led other nations in these numbers, but this graph shows only gradual growth in the US and dramatic growth in China. In fact, China now leads in producing natural sciences and engineering degrees, and the US stays ahead in total degrees only because the count includes degrees in the social and behavioral sciences.[35]

These numbers are part of a long and evolving story of US leadership decline compared to its competitors. In 1975, the US had a huge lead over Europe and Asia in the number of natural S&E doctoral degrees, awarding more than twice as many as the other two regions combined. However, by 1999, the US was in third place, surpassed by both Asia, which was on a strong rising curve, and Europe.[36] Since then, the playing field has leveled.

If Romer is right, and the talent base is key to innovation and therefore growth, then the US needs to keep up with its competitors in S&E degrees. Figure 1.6 shows the numbers of international students in S&E fields enrolled in US colleges and universities, both as undergraduates and graduate students.

More international students come to the US than any other country. While they earned only 7 percent of US undergraduate S&E degrees in 2019, they made up 49 percent

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of students earning US graduate S&E degrees. During the 2012 to 2020 period, the biggest increases were in engineering and computer science; in 2019, students earned 50 percent and 57 percent of master's degrees in those fields, respectively. The coronavirus outbreak in 2020 led to a 20 percent decline in these international S&E students from the previous year, although the numbers recovered by 2023.

Clearly, the US has become very dependent on international students to staff its science enterprises. But this is not a new story: this country has long depended on its ability to attract foreign talent in its innovation system—since at least the turn of the twentieth century. It has been a major competitive advantage. If one nation is nurturing talent only within its own borders and another is drawing talent in great numbers from across the globe, what does Romer's prospector theory tell us about which one will mine more technological gold?

Of course, any competitive advantage gained through international students depends on their willingness to stay in the US and work after graduation. US visa and immigration laws do not make this easy, and it became more difficult during the Donald Trump administration, despite occasional rhetoric by politicians about the need to "staple green cards to STEM [science, technology, engineering, and mathematics] graduate diplomas."[37] A 2015 National Science Foundation (NSF) survey of foreign recipients of US S&E degrees found that more than two-thirds wanted to stay, and that about 45 percent had firm plans to do so.[38]

We need to acknowledge that while US universities since the end of World War II have excelled at scientific education and research compared to many foreign academic competitors, this gap is also narrowing as foreign academic institutions grow and improve. A US science degree is not quite as magical as it once was.

This review of the S&E opportunities that foreign students can help with does *not* imply that the US shouldn't do a much better job at encouraging our domestic population, including women and minorities, to go into S&E careers. It must. Workers in STEM have higher median earnings and lower unemployment than non-STEM workers: in 2019, the median annual salary difference exceeded $22,000 a year, and unemployment levels for STEM workers were half those of non-STEM workers.[39] The number of STEM jobs has grown faster than non-STEM jobs, and this difference is projected to continue.

Minorities, however, remain underrepresented in degrees from S&E fields. And while women earn 57 percent of all bachelor's degrees and about half of all S&E bachelor's degrees, their participation in graduate S&E degree programs is mixed, and lowest in engineering, computer science, and physics.[40] These problematic numbers represent limits on opportunity and restrict the innovation system's access to a significant talent base.

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There is another dimension that also needs to be noted. We have been discussing the talent issues in terms of college degrees and postgraduate S&E degrees. But a skilled technical workforce peopled with workers who have two-year degrees or skill certificates is a vital input into productivity as well, and as detailed in chapter 11, there has been a systematic underinvestment in this workforce by federal and state governments.

Overall, again assuming that Romer is correct about the importance of the talent base to innovation, and therefore to growth, these numbers suggest future problems for the dynamism of the US economy—unless they are continuously improved. Issues of the US science talent are explored in more detail later in this book.

MAJOR POINTS

Let's review the major points in this chapter. Robert Solow, the leading proponent of economic growth theory, made a convincing case, based on a review of a half century of US economic history, that "technology and related innovation" was the key to some two-thirds of the country's economic growth. His focus on technological innovation spurred a new dynamic growth theory, in sharp contrast to earlier theories centered on capital-supply, labor-supply and savings factors in a more static and cyclical, equilibrium-based concept of growth.

Paul Romer, building on Solow's theory, added a second critical factor to growth theory: "human capital engaged in research." He argued that this talent element was the key behind the development of Solow's focus on technological innovation.

The dramatic growth of the US economy in the 1990s appears to track with both economists' causative factors. The computing and IT breakthroughs that came to fruition in the 1990s, according to the economist Dale Jorgenson, clearly powered the dramatic productivity gains and growth of that period.

How do investors look at this? A 2000 report written at the end of this growth burst for potential investors by analysts at a major Wall Street investment house offers additional insights. It shows that the investment community understands the role of technology breakthroughs in powering growth. So business buys the Solow and Romer theories. The report, though, also vividly illustrates that the established investment community is prepared to support only the latest stages of technology development. Early R&D stages will not receive private-sector, market-based support and have to rely on government R&D funding.

What about that federal support? Although R&D investment arguably is a direct innovation factor behind Solow's connection of technological innovation to economic

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growth, US federal R&D support as a percentage of GDP has been in an ongoing decline. While federal support for R&D in the life sciences has been accelerating, support for R&D in the physical sciences has been in serious stagnation and disarray.

Romer's connection of talent to innovation and, therefore, to growth is the second direct innovation factor that we focus on—and its picture, too, is not reassuring. US leadership in building its science talent base has been declining against key economic competitors. Over time, this will likely affect the talent base needed for our innovation system.

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2 INNOVATION SYSTEMS AND DIRECT AND INDIRECT INNOVATION FACTORS

The words "innovation" and "innovate" are often used in the simple sense of creating something new. Here, however, "innovation" has a larger and more specific sense: as a system for research, invention, and development, built on scientific discovery and breakthrough inventions, to apply science and technology to spread advances into commercial or societal use. Put more succinctly, innovation operates at the intersection of science and invention to create social and economic value.

Innovation, then, is a much larger concept than invention, which represents only a single new technology. Innovation includes a critical invention or a group of inventions of new technology *and* the bundle of applications around that technology that expand its reach. So innovation is a system of technology advances and applications of these technologies, as well as related new products, processes, and ways to organize for the innovation.

Let's make these abstractions real. What does innovation look like?

It's 1878 and 1879 in rural Menlo Park, New Jersey. Thomas Edison and a team of artisans, engineers, and a couple of scientists work at all hours, and sometimes around the clock, in front of a pot-bellied stove in a hundred-foot-long wooden frame building. It looks like a simple warehouse next to a plain farmhouse. Edison calls it the "Invention Factory."

At night after the long workdays, they bake pies on the stove, sing songs, and shout doggerel poetry at each other. After testing more than 3,000 designs, they develop a practical light bulb—but it's useless without the electrical infrastructure to support it. In an act of genius more than equal to the light bulb, Edison and team then develop all the key elements of this electrical infrastructure, from generators, to wiring, to transmission systems, to insulation, to fire safety, to power stations, to the way to organize the electric

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utility industry, and then they develop a viable economic model that encourages Wall Street and Edison's supporter, J. P. Morgan, to finance his entire electricity innovation system.

Another example: The steam engine is the initial invention, but locomotives, tracks, iron and then steel rails, coal, switches, couplings, air brakes, railroad yards, and even our national system of uniform timekeeping are all part of the innovation of railroads. Technologies are the bones on which an entire innovation organism is formed.

This Edison lesson in the innovation process makes clear that we need to understand technology development better. Technology evolves in a series of stages:[1]

- Technology visioning
- Enabling technologies (e.g., the scanning tunneling microscope for nanotechnology, as noted in chapter 1)
- Technology idea
- Research
- Early-stage engineering development
- Late-stage engineering development
- Testing and demonstration of prototypes
- Production/manufacturing design
- Pilot production/manufacturing of the selected prototype (the invention)
- Commercial production (for a demonstrated initial market), including driving the production cost curve downward to improve manufacturability and reduce costs
- Supporting the product infrastructure system
- Additional applications (e.g., the internet as an application for personal computing)
- Second, third, and fourth generations of products (and beyond) with incremental improvements

Despite this orderly, logical-looking list, it must be stressed that technology development is not a neat, linear process. The steps may not occur in this order; there may be many backward steps; steps may interact and merge; different players may develop different steps, enabling other players to skip them; the process tends to multiply in cost with each step; and accidents and failures occur throughout. But this provides a working list to begin with.

There are also different models for technology change. Innovation can occur from *technology push*: a new technology evolves and, in itself, creates new markets for new products. For example, the atomic bomb grew out of an obscure area of physics understood by only a few dozen physicists before World War II. It may or may not have ended

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that war, but it certainly has transformed geopolitics through the present day. Nuclear power was its side product, initially promising endless cheap energy and currently promising clean energy in a period of climate change. The research pushed atomic weapons technology, which in turn pushed the innovation of atomic power.

Another example is microwave theory, which led to the development of radar during World War II. After the war, that led to the microwave oven and communications technology.

Innovation can also occur from *market pull*: the demands on technology for products that the market wants, forcing technology development. Generations of broadband technologies, digital subscriber lines (DSLs), Wi-Fi, and the cable modem evolved through this model.

Technology development may be incremental or radical. *Incremental technology innovation* typically improves the function, aesthetics, performance, efficiency, manufacturability, dependability, and repairability of an existing technology. An ongoing stream of incremental improvements can multiply a technology's productivity and sustain a firm's competitiveness for decades. Think how about aircraft evolved from the Wright brothers' powered kite through the jet airplane of today. *Radical technology innovation* is groundbreaking and transformative: it breaks the mold, represents disruptive change that can displace earlier and established technologies, and can create a focus for a new innovation direction and the corresponding major productivity gains. Think of the Wright brothers' airplane prototype on the beach at Kitty Hawk. Radical innovation can be a growth accelerator, while incremental is a growth improver.

John Holland, a first-generation computer scientist and student of complex systems from the University of Michigan and the Santa Fe Institute,[2] coined the terms *exploitation learning* and *exploratory learning*. Exploitation learning refers to improvements within the networks and systems that you already have, while exploration learning is taking major risks to create new systems and networks. Since innovation fundamentally involves learning, these terms help explain the differences between incremental and radical technology development.

Radical technology innovation can yield a disproportionate profit impact for firms that introduce it.[3] The great majority of product launches by firms are incremental; only a modest minority are radical. Of the incremental (or "me-too") advances, most have a positive revenue effect for the launching firms, while many fewer of the radical (or "value") advances have a positive revenue impact. The radical advances, though, can be far more profitable than incremental advances—which is where the story becomes interesting. Arguably, this same profit—that is, growth—impact may accrue to nations capable of launching radical technology innovations.

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While radical technology innovation may have a much greater potential payoff than incremental, radical is much more difficult. With incremental, many of the developmental steps listed in this chapter can be skipped, especially the tougher earlier ones. Radical is more about invention, and incremental is more about engineering.

The economist Joseph Schumpeter described "creative destruction" in capitalism and competition, and the business analyst Clayton Christensen described how "disruptive technologies" from radical technology innovation can disrupt existing markets and force new ones.[4] Because radical technologies may disrupt their own markets, they are much more difficult for established firms to develop. Radical technology development contains a potentially large element of self-destruction, and even a death wish that is hard for established firms to cope with—and there are lots of examples. The Bell Operating Companies stalled the implementation of true broadband because it potentially meant ending their local telephone service monopolies. When the Defense Advanced Research Projects Agency (DARPA) at the US Department of Defense (DOD) first sought developers for what became the internet, AT&T and IBM were not interested because it would disrupt their telephone communications and mainframe computing business. Lockheed Martin and IBM had to set up virtual companies within their companies to do some of their most important radical innovations, Lockheed through its famous "Skunk Works,"[5] and IBM through a separate and isolated development group for the personal computer (PC).[6] These examples help explain why radical innovation in the US has tended to be a province for smaller firms and entrepreneurial start-ups that have less to lose than the larger, established firms.

It is important to remember that *both* radical and incremental technology innovations are crucial. Would you have even thought about flying across the Atlantic in the Wright brothers' aircraft, a radical technology? It takes generations of incremental advancement to get us to Boeing's 787. Creation is beautiful, but so is evolution. Even though the radical has a certain romance, both capabilities are indispensable.

Overreliance on incremental technology innovation for much of the past century gave rise to what is often termed the *traditional product cycle theory*, which generally includes these elements:[7]

- The firm defines the product.
- The market develops.
- One design dominates.
- The number of competing companies is reduced.
- The product becomes a commodity (i.e., high volume, price drops, low profit margin, no longer unique).

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- Production technology often goes offshore to lower-cost producers.
- Barriers to entry increase.
- A surviving firm has:
  - The capacity to advance the technology
  - Large-scale production
  - Strong distribution and marketing
  - Management talent to grow the firm

There is an argument that this product cycle theory is now breaking up. It applies only to traditional manufacturing, not to the emerging world market for *services*. Even within manufacturing, *globalization* is spurring competitiveness worldwide, which speeds the product cycle and the export of manufacturing. This may be forcing companies of all sizes to learn how to *create and incorporate radical technologies on a continuing basis*. Superiority in *design* is becoming critical in global competition, and firms learning to master this can disrupt the discipline of the product cycle. There is also growing talk, explored in chapter 9, about advanced manufacturing, a *rebirth of manufacturing technologies and process*. A productivity leap through new manufacturing processes can redraw the competitiveness picture and enable higher-cost producers to compete.

Indeed, *a new combined model* is emerging, in which firms combine a very sophisticated element, information technology (IT)–based services, with *advanced manufacturing*, leading to new types of firms that break down the traditional product cycle. The competition is ever fiercer, forcing both changes in the model and new models.

NATIONAL INNOVATION SYSTEMS AND INNOVATION ACTORS

The nineteenth-century economist David Ricardo developed a theory of *static comparative advantage* to explain that a nation could develop a competitive trading advantage based on its natural resources. Ricardo's famous example portrays England trading with Portugal. England has limited sun but a lot of rain; it, therefore, has a lot of grass, so it raises sheep and produces wool. Portugal has a lot of sun; it produces many grapes and much wine. England can't produce wine, so it sells wool to Portugal, and in turn, Portugal—which has less green grass—sells its wine in exchange for wool. Each nation seeks and takes advantage of its comparative advantage, and a wonderful equilibrium occurs in which both trading partners emerge as winners.

This is the heart of free trade theory. It is a static model; since this nineteenth-century trade is centered on natural resources, the comparative advantages between the trading partners are fixed.

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By the second half of the twentieth century, *dynamic comparative advantage* emerged. As resource-based economies were surpassed by technology-based economies, the US led the world in creating a model of dynamic advantage through investments in research and development (R&D), technology development, education, transparent markets, efficient governance, and other areas. Particularly in the 1990s, the US sought comparative advantage through leadership in the *early* part of the traditional product cycle, which led to the innovation stage.

Unlike the resource-based economies, innovation-based competition is not inherently static; it is dynamic and can be created or captured by others. Technology-based firms see this happen every day in their sectors, so why shouldn't nations?

Richard Nelson of Columbia University, another of the founders of the growth economics school, was a leading analyst of this shift to dynamism. He evaluated the idea of *national innovation systems* in a 1993 book by the same name.[8] He was not, however, the first to use the term; in a 1987 book comparing Japan's system, the British economist Christopher Freeman defined it as "the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies."[9]

The concept is implicitly about this issue of dynamic comparative advantage. At the heart of Nelson's arguments is his perception that "technological capabilities of a nation's firms are a key source of their competitive prowess."[10] Up front, he asks a critical question in an era of transnational corporations: Does the term "national innovation systems" make any sense? He argues in the affirmative, as we will explore.

Defining innovation in a broad sense as "the process by which firms master and get into practice product designs and new manufacturing processes,"[11] Nelson dives into a review of "Schumpeterian innovators." He notes that Schumpeter's "creative destruction" occurs via innovation and finds that it's not necessarily the first innovator that captures most of the economic rents associated with the particular innovation. Therefore, a competitive nation must be concerned not only with the initial innovator, but also with fostering a broader "innovative capability." He argues that his concern can't be limited simply to firms or to science research, but rather must focus on a "system" of "institutional actors" that influence innovative performance. He asks about "the way technical advance occurs . . . and the key processes and institutional actors involved." His answer is that it happens through science and trial-and-error learning.

There is, therefore, a variety of institutional actors in an innovation system, including universities, firms, government agencies, and related governmental policies. If there is a common way that technical advancement occurs, effected by comparable institutional actors, Nelson argues that there is a "common analytical framework" across nations.

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Nelson identifies science as a significant factor because "new science gives rise to new technology." We can define science as understanding the natural world. It evolved out of the "natural philosophy" of the sixteenth to nineteenth centuries; it is inherently observational, watching the natural world; and it is discovery oriented. In contrast, technology is the system to organize scientific and technical knowledge to achieve a practical purpose. Its systems include technical advances plus models to implement those advances, so they move from observation to implementation.

Science and technology can be both leaders and followers—a critical point to consider as we delve into the organization of innovation systems. Nelson cites several examples of science leading to technology advances: Michael Faraday's 1831 model of electromagnetic induction as one element that evolved into Edison's electric light and gramophone; Alexander Graham Bell's telephone; and Heinrich Hertz's concept of radio waves, which led to radio and television. He notes further that neither Faraday nor Hertz were looking for the subsequent applications of their theories.

Nelson also points out that science can evolve out of technology application. There are numerous examples. Alchemy, tanning, and brewing are early practical applications that later gave rise to scientific principles. The German chemist August Kekulé's work in the 1860s on the molecular structure of benzene led to organic chemistry. Polymer chemistry grew from industry applications. Chemical engineering itself was an interdisciplinary merge of chemistry and mechanical engineering, and science followed the numerous practical advances in this area. Out of the workings of steam engines, the nineteenth-century French mechanical engineer Nicolas Léonard Sadi Carnot developed the second law of thermodynamics. Aerospace engineering evolved from the practical work by two brilliant bicycle mechanics to develop powered flight. The World War II pressure for computing to solve decoding and artillery ballistics problems yielded the foundations of computer science.[12] Lasers and optical fiber yield the science of optics. The first transistors yield semiconductor physics. The list goes on and on.

So there is a rich and complex interaction between science and technology—science yields technology, but technology applications can yield science as well. Because of this interaction, an innovation system arguably demands both science and technology leadership. A point that we can derive from Nelson's observation is that technology development needs to be organized as a two-way street.

There are further limits to science's role in technology evolution. Innovation in technology involves not only invention but design, choosing the right "cluster of performance characteristics," as Nelson puts it.[13] In addition, most industrial R&D spending is on incremental technology advances: propellers evolve into jet turbines; and canvas skin on a wooden air frame becomes aluminum skin on aluminum or titanium frames. As

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suggested previously, the process of incremental advancement is not the process of scientific breakthroughs, but it is important in its own right.

Returning to Nelson's other key point about innovation systems, he finds that innovation's "institutional actors" involve a mix of players, in addition to scientists, which leads to a review of the range of typical innovation players in innovation systems. His understanding that industry is central to innovation focuses his list of innovation actors around industry's needs. Nelson's roster includes the elements described in the following sections.

INDUSTRY LABS

By World War I, industrial research labs proliferated in major industries, staffed by university-trained scientists and engineers and dedicated to incremental advances and inventions.[14] These innovation actors are more important than university or government labs, he argues, because after the initial technology is in place, industry users of that technology have a detailed knowledge of the technology's strengths and weaknesses that transcends the general public scientific knowledge. Industry R&D is only one part of a larger industry innovation picture that also includes management and organization, including for R&D itself.

US industrial labs have declined in strength since Nelson wrote in 1993, led by the demise of the most famous, Bell Labs, following the breakup of AT&T.[15] But a significant industry R&D role remains even if some of the most famous labs have faded. While Romer argued that "human capital engaged in research" was behind innovation, Nelson's work, drawn to its logical extension, suggests that to understand innovation, we must broaden Romer's scope. It's not only researchers; technologists and engineers are also key to the talent base behind technological innovation. Nelson implies that in many nations, engineering constitutes industry R&D; it's not just about the "R," but also the "D."

UNIVERSITY LABS

Historically in the US, there has been a working connection between the modern industrial lab and the modern research university, which grew up as companions and partners. In the 1860s, MIT's first president, William Barton Rogers, pioneered the concept that science education must be lab-based, and MIT's subsequent history is replete with such examples.

Again, while major industry labs have declined, industry R&D continues, and many industry start-ups now come out of university labs. Nelson notes that academic science fields are oriented not only to basic research, but some also are oriented to applied

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science, including material science, computer science, and engineering. The overwhelming bulk of US university research is federally funded.

Although research universities can support technical advances, there are multiple issues to explore regarding how successful the connecting channels between industry and university research are.

GOVERNMENT LABS

In the US, government labs play an important role in many technologies; advances emerge from agriculture, health, energy, and defense labs that are directly funded but typically indirectly run by government. In other countries, government labs often substitute for university labs.

PUBLIC-SECTOR SUPPORT FOR INDUSTRY RESEARCH AND DEVELOPMENT

While public-sector support for basic research at universities and government labs is the story typically told, there is also such support for industry R&D in certain areas. Because the DOD funnels most of its R&D funding to industry-led R&D efforts, this is a major element of the US innovation system, and the results often spill over into civilian sectors. In few other countries, however, does a defense role dominate industrial R&D as in the US; many, such as Japan and Germany, simply support industrial research at firms, and not through an explicit national security justification. In addition to defense, there is a strong history of US government support for applied agricultural research.

INNOVATION ACTORS

Nelson recognizes that there are major differences in innovation actors across different industrial sectors; there is no standard model. The mix of actors can be affected by demands for advances from suppliers or customers. In complex technologies, the supply chain and customers and users play important roles in innovation, as do component and systems producers. Therefore, there can be "innovation networks" at the industry level among industry segments, as well as among the other innovation actors.

Nelson's discussion of *innovation actors* is a vital one. Innovation is a highly complex process deeply tied to the evolution of ideas and their testing and evaluation among many participants. Just as you can't put on a stage play without actors, you can't innovate without innovation actors. Nelson's initial list of such actors gives us a key clue to how to analyze the capability of innovation systems: figure out the playbill, who the actors are, and evaluate their strengths and weaknesses.

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Analysis of innovation actors is an important tool for Nelson as he makes his case that there are national systems of innovation. Looking at the US innovation system from 1945 to 1975, he includes the following elements. First, US firms were larger in scale than any other country's at the time because they had been serving continental-sized markets.[16] US firms in that period spent more on R&D, and in turn, the federal government spent more on industrial R&D, through its defense mission, than competitor nations. In significant part due to World War II–era defense R&D spending, and because that spending continued during the Cold War, US research universities were stronger than any others in the world. Despite large gaps, they were also better connected to industry than universities elsewhere, largely due to the wartime and Cold War R&D spending. Because the US was rich in natural resources, and because the continental US market was huge and integrated, US firms focused on selling into that market; they had only a limited export orientation in the 1945–1975 period.

Japan's innovation system in the 1970s and 1980s stands in contrast. Because Japan was resource poor, it understood from the 1870s onward that it had to export to finance its industrialization.[17] That powerful export orientation remains to this day. Japan's integrated keiretsu—its conglomeration of businesses linked by cross-shareholdings to form a robust corporate structure—initiated strong industrial R&D programs, while its university research was relatively weaker. Postwar firms in Japan were encouraged to undertake R&D, particularly applied R&D, and received extensive direct R&D, as well as technology development support, from the government's Ministry of Industry and Trade (MITI), now called the Ministry of Economy, Trade, and Industry (METI), which had an explicit technology policy while such US policy was implicit.[18]

Nelson argues that there are differences between national innovation systems based on various underlying economic national patterns. Large, high-income countries tend to have a large fraction of their economies in R&D–oriented industries. High-income nations with limited natural resources (Japan, Germany, and South Korea) share a strong export orientation. National security is imputed and connected to the innovation system in the US, Britain, and France, where defense R&D has constituted the majority of government-supported R&D. In the US and Britain, only a limited governmental industrial policy R&D role exists outside defense R&D. Low-income countries pursuing development, along with resource-limited, export-oriented countries, generally feature a major industrial R&D role by the government. These are all examples of factors leading to differing national innovation systems.

Nelson's research concludes that strong firms—not necessarily large, but with strong R&D programs—are the key factor in achieving national innovation success. These firms must become highly competent in

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- Product design
- Management
- Meeting consumer needs
- Linking to upstream suppliers and downstream markets (i.e., users)
- Accessing investment
- Competing in world markets
- Undertaking the bulk of their innovation (meaning both incremental and invention-based advances) internally (and not through intellectual property purchases or mergers, and regardless of whether the firm is networked to other innovation-oriented firms)

Nelson summarizes a series of other elements, not equivalent to his point about innovation actors but still important to innovation success:

- *Education and training*—Implicitly echoing Paul Romer, Nelson notes that science-based industry depends on university-educated researchers and technicians, and there is a role for central governmental education support. High-tech sectors, in particular, require university-educated workforces, both in and out of R&D. He cites South Korea and Taiwan as having education-led growth policies.
- *Fiscal, monetary, and trade policy*—Governments control these policies and must get them right.
- *Public support of university or government laboratory research*—Nelson believes that these are critical to key fields, such as electronics. For university or government labs, interaction with firms or groups of firms and particular researchers or research programs is important. This enables a "technological community" in significant fields. Defense research was vital to US success in such areas as electronics, computing, aerospace, and semiconductors. However, there is now "declining spillover" between defense and the commercial sectors on which defense needs depend because the US military has shifted its emphasis in the post–Cold War period away from supporting new generic technologies and more to specific hardware. Nelson implies that low levels of public industrial R&D funding outside defense may be an increasing problem for US innovation.
- *Government support for industry technology innovation*—This is the most controversial item on the list, and it is discussed in more detail next and later in this chapter.

Concerning this issue of explicit government support for high-tech innovation, as Nelson phrases it, he recognizes the role of US defense R&D and of government-tech sector cooperation in other countries in this area. Although he has reservations about

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government's ability to get its role right consistently, he also sees potential advantages. He notes high-technology advances have been important to high wages, high skill levels, and top competitive management ability. He sees creating systematic technological advancement in a series of fields as a reasonable innovation system goal, noting that in addition to the industries producing the technology innovations, much value occurs in downstream industries incorporating these advances. He concludes that active governmental policies can be effective in generating competitive advantage in technology sectors and have the advantage, if industry-led, of being comparatively low cost. Overall, advances in key technology areas are building blocks for both an economy's upstream and downstream industries, in addition to the tech sector itself.

DIRECT INNOVATION FACTOR 3: INNOVATION ORGANIZATION

Nelson offers a number of important ideas, but two in particular stand out for our purposes. First, he argues that there are *national innovation systems* that vary from country to country depending on national economic circumstances and economic history. Second, he presents a key tool to analyze both national innovation systems and innovations systems in general: the concept of *innovation actors*.

The work of Solow and Romer discussed earlier led us to the concept of *direct innovation factors*; Nelson adds to the factor menu. Reviewing the composition and strengths and weaknesses of innovation actors provides a working framework for comparing and evaluating innovation systems. Importantly, building on his points about innovation systems and innovation actors brings us to our third direct innovation factor: *innovation organization*.

Solow's "technological and related innovation" underscored the importance of R&D for innovation——our first direct innovation factor. Romer's concept of "human capital employed in research"—the talent base behind that R&D system—provides our second, talent. The idea developed from Nelson's work, *innovation organization*, gives us our third. It can be defined as the organization and connectedness of the institutions involved in R&D and technology development and its implementation to further innovation in an economy. Effective innovation organization, coupled with the other two factors, enables formation of a strong innovation system.

Nelson's work on national innovation systems, analyzing innovation actors as more indirect factors, is now widely echoed. We see this in the World Economic Forum's *Global Competitiveness Report,* which has been issued annually since 2004. The 2020 report considers elements in its rankings that illustrate the complexity of the systems that we must begin to understand.[19] The report evaluates nations' "Enabling Environment" (including

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governmental institutional strength, debt levels, tax bases, and adoption of digital technologies); "Human Capital"; the strength of "Markets"; "Innovation Ecosystem" (including R&D investment, venture capital [VC] availability, and incentives for patient capital); and "Transformation Readiness."

Nelson's initial look at innovation systems and the World Economic Forum's shotgun approach to overall competitiveness are indications of the worldwide search, among developed and developing nations alike, for the formula for economic growth. Without the two direct innovation factors discussed in chapter 1—R&D and the technology talent behind it—innovation would be a chimera. It could not happen. Nelson's idea of innovation actors allows us to break down these two factors.

There are clearly big public- and private-sector roles in each factor, but we need more detail, some elementary categorization. Beginning with the public-sector side (the government) and using the US as the example, a working list of some of the categories of innovation actors that the federal government supports in the R&D area (the state and local governmental R&D role is still modest) include the following:

- University R&D
- R&D at government labs
- Government-supported industry R&D (principally through DOD mission-oriented R&D)

With respect to the federal role (as opposed to the major state and local governmental roles) in education, there are additional actor categories:

- Science and technology fellowship/scholarship grants and loans for students at the undergraduate and graduate levels
- University science and technology R&D awards (which directly support graduate education)
- Federal K–12 education support
- Federal workforce education programs for technician-level workers through US Labor Department programs and US Department of Education Pell Grants that help support community colleges

There are comparable lists for these two direct factors on the private-sector side. For R&D, there are

- Industry R&D (including both radical and incremental research at both large and small firms)
- Industry early- and late-stage development, prototyping, and scale-up to production

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For talent, there are

- Worker technical training programs
- Executive management training, particularly related to technical areas

Nelson's work led us to the third direct innovation factor, innovation organization, which is how an innovation system and the institutions within it are organized to enable innovation. For the federal government, these would include

- Federal basic research agencies
- Federal applied research organizations (including Defense, Agriculture, and, increasingly, Energy department programs)
- Federally funded research universities

In the private sector, the innovation organization list would include

- Industry labs and company-based R&D programs
- Industrial research organizations and consortia

These lists are only a starting point; in each industrial sector, the elements grow in complexity. Now let's add to the complexity of the system. Nelson's working list suggests that there are other factors in the complex web of a national innovation system that we need to consider, aside from the three direct factors. Again, using the US as an example, let's call this additional bundle of factors *indirect innovation factors*.

INDIRECT INNOVATION FACTORS AND AN INNOVATION FRAMEWORK

Indirect innovation factors influence the dynamism of a national innovation system, but more indirectly and implicitly than the direct factors cited previously. In other words, innovation can occur without them, but they help. If you get them right, they can be innovation contributors to varying degrees, and if you get them wrong, they can create innovation barriers.

Each of these factors carries its own mix of indirect innovation actors. Again dividing the factors into public- and private-sector categories, and using the US as the model, a partial list for the government includes

- Fiscal/tax/monetary policy
- Trade policy
- Intellectual property protection and access
- Technology standards

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- Technology transfer policies
- Government procurement (particularly for R&D mission agencies)
- Legal/liability system
- Regulatory system (for environment, health, safety, market solvency, market transparency, financial institutions, etc.)
- Accounting standards (through the Securities and Exchange Commission and Financial Accounting Standards Board)
- Export controls

The private-sector indirect innovation factors include different but vital elements, and each carries different sets of innovation actors:

- Investment capital—angel, venture, initial public offering, equity, and lending
- Markets—securities markets, product markets, etc.
- Management and management organization for innovation and that affect the competitive quality of firms
- Talent hiring, compensation, and rewards (for innovation-related talent)
- Trade secrets

This discussion amounts to a new framework for understanding innovation. To summarize, I have argued there are at least three direct innovation factors: you must *perform R&D*; you need a strong *talent base* to perform it; and you need to see *innovation as a system*. The strength of that system will be determined by the capabilities and connections of the institutions and organizations within it. In other words, innovation will not just happen because you undertake R&D and have talent; you need innovation organization as well. We will explore other innovation factors as this book progresses, but these three are at the core, and innovation will not occur without them.

Direct innovation factors are not the whole story; there is a host of additional factors, *indirect innovation factors*, supported by both the public and private sectors. While less critical than the direct factors, strong innovation economies need to get as many of these indirect factors headed in a positive direction as possible.

Figure 2.1 sketches out a basic, oversimplified working framework of this complex system, one that is dynamic and evolves and in which the factors will shift and change.

To illustrate both the complexity and the integrated nature of the innovation system, let's briefly review several examples of indirect innovation factors.

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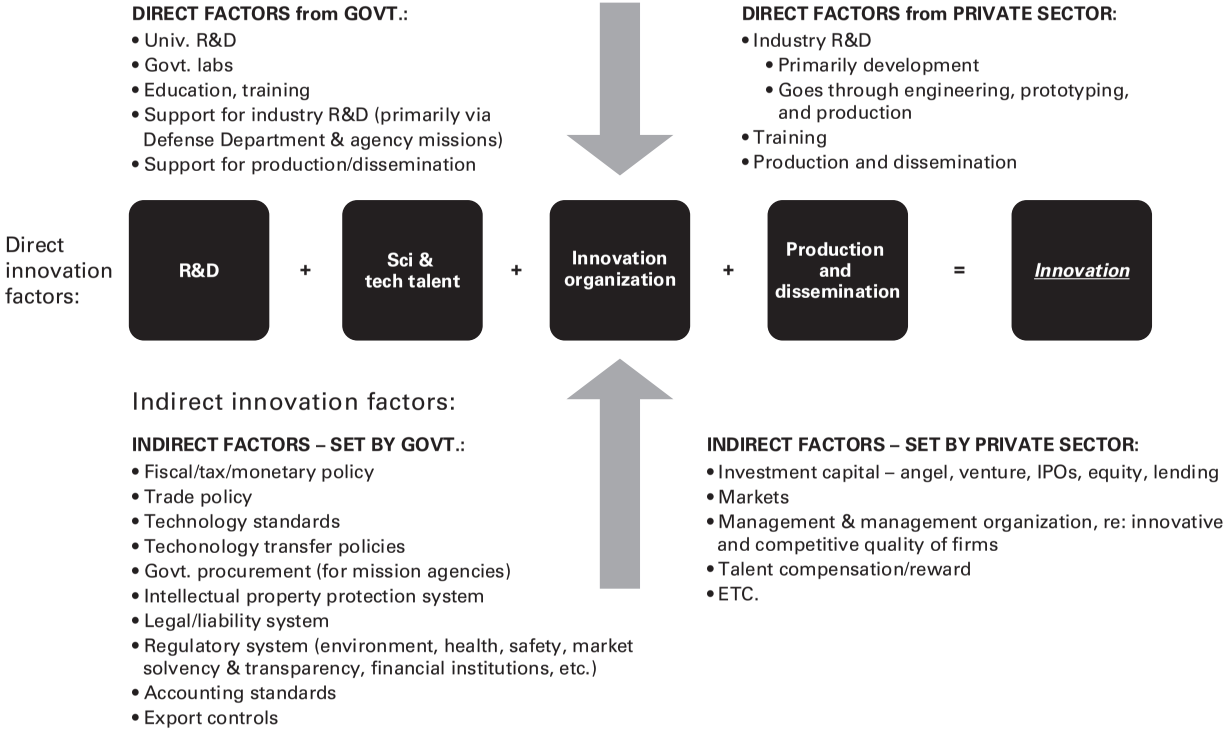
DIRECT FACTORS from GOVT.:
• Univ. R&D
• Govt. labs
• Education, training
• Support for industry R&D (primarily via Defense Department & agency missions)
• Support for production/dissemination
DIRECT FACTORS from PRIVATE SECTOR:
• Industry R&D
• Primarily development
• Goes through engineering, prototyping, and production
• Training
• Production and dissemination
Direct innovation factors:
R&D
+
Sci & tech talent
+
Innovation organization
+
Production and dissemination
=
Innovation
Indirect innovation factors:
INDIRECT FACTORS – SET BY GOVT.:
• Fiscal/tax/monetary policy
• Trade policy
• Technology standards
• Techonology transfer policies
• Govt. procurement (for mission agencies)
• Intellectual property protection system
• Legal/liability system
• Regulatory system (environment, health, safety, market solvency & transparency, financial institutions, etc.)
• Accounting standards
• Export controls
INDIRECT FACTORS – SET BY PRIVATE SECTOR:
• Investment capital – angel, venture, IPOs, equity, lending
• Markets
• Management & management organization, re: innovative and competitive quality of firms
• Talent compensation/reward
• ETC.

FIGURE 2.1
The innovation framework: Direct and indirect innovation factors.

INDIRECT INNOVATION FACTOR EXAMPLE 1: ACCOUNTING SYSTEMS

What some call the "old economy" (roughly before the IT scale-up of the 1990s) focused on the management of tangible assets—capital plant, equipment, physical resources, and inventory. The twenty-first-century US economy is arguably shifting to new foundational elements based on intellectual, nonphysical, intangible assets that indicate the innovation capacity of firms.

Accounting systems are key to valuing innovative firms, and so they constitute an indirect innovation factor.[20] Yet our accounting system, which drives transparency and therefore investment valuation for firms, still measures the old, tangible economy—and thus it tends to undermine the willingness of firms to invest in knowledge-based innovation. It limits the ability of investors to measure actual value for knowledge-based firms; they are limited to assets that are now only a modest part of the actual value of most modern firms. In recent decades, stuck with a problematic valuation system, markets increasingly focused on measures of short-term profitability, which are not an adequate indication of a firm's longer-term innovative capacity.

Are we really shifting to a knowledge-based economy? A report from the National Innovation Initiative prepared by Egils Milbergs—a thought leader on this issue—and some of his colleagues summarizes data indicating that US firm investment in intangible assets (R&D, business processes, and software) reached $1 trillion a year by 2002. That compares to $1.1 trillion invested in tangible assets in the US manufacturing sector. Reviewing securities market data, 82 percent of the market value of US firms in 2002 represented intangible assets, and only 18 percent could be attributed to tangible assets. Ten years earlier, in 1992, the intangible value was 62 percent; 20 years earlier, in 1982, the intangible value was 38 percent.[21]

These trends have been accelerating. By 2014, investments by US firms in intangibles were nearly twice that of tangibles.[22] Take Tesla, the leading US electric vehicle (EV) maker. Its market capitalization in early 2022 was nearly $1 trillion, larger than the value of the top five world carmakers combined, and yet in 2021, it produced only 936,000 vehicles—a modest fraction of the total US vehicle production of 8.8 million.[23] It clearly is not being valued based on its tangible assets. The only explanation for its valuation is that the markets are measuring an intangible—namely, its capacity to outinnovate competitor automakers by leading the way to electric vehicles, battery advances, and supporting integrated power systems.

There is now a significant positive correlation between US firms attempting to undertake preliminary intellectual capital disclosure, for example, and higher market capitalization.

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The Milbergs-led report argues that we need new accounting metrics for how firms invest in qualitative innovation factors that are sustainable for the long term.[24]

What would an investor want to know about a company in the knowledge-innovation-oriented economy? Keep in mind the factors in the framework shown in figure 2.1, particularly those relevant to the private sector. We already have data on total company R&D investment and company patent filings, but these data don't tell us, for example, how a firm divides its research portfolio between R&D or between radical and incremental research. While market value and profitability say much about success in bringing on innovations in the past, we should think hard about other ways to measure innovation capacity. For instance, we could begin to work on talent metrics that tell us employee education levels (including, but not limited to, R&D employees) and ongoing education and the focus and success of employee recruitment (including for R&D talent). More broadly, we could seek ways to benchmark firms against industry innovators, using measures such as incorporation of advanced production processes (including through past, but still relevant, industrywide standards such as Six Sigma and ISO 9000, and through today's advanced manufacturing technologies such as digital production systems). Benchmarking on how firms are adopting computerized systems and energy efficiencies could also be relevant. Since we are seeing that innovation occurs in a system with numerous innovation actors, data could also be sought on ability to access external R&D, such as on firm participation in technology alliances and networks with suppliers, customers, users, competitors, and university and government R&D projects.

These categories, however, represent guesswork. We need to move from guesswork to rigorous accounting metrics.

To summarize, we're currently measuring twenty-first-century firms with nineteenth-century benchmarks. This means accounting, which is the first indirect innovation factor and drives so much of investment, is weak.

Suppose that we had accounting metrics that better measured intangibles. Rather than markets driven by guesswork about intangibles and innovation based on short-term returns, we could start to drive investment in more transparent and accurate measures of innovation capacity. Think of the marketplace power that would bring into innovation investment.

The US has embarked on some fitful starts to develop better accounting metrics for innovation capacity; the European Union has begun a much more systematic study.[25] The underlying point here is that accounting standards are not directly responsible for innovation; they are an indirect, not a direct, innovation factor. But if we get them right, they could provide a useful spur to innovation—because sound information and transparency drive sound market investment, including into innovation.

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INDIRECT INNOVATION FACTOR EXAMPLE 2: VENTURE CAPITAL

We discussed earlier in this chapter how capital investment is an important handmaiden to innovation, not a substitute for it. The VC segment of our investment/financial services sector grew to fill a gap in innovation investment, funding start-up, innovation-oriented, entrepreneurial ventures. It was built around an idea that previously has been noted: introducing new technologies potentially delivers much higher investor returns than the normal flows of the equity stock market. VC is not itself innovation, but it can be an important innovation support mechanism, so it is a significant indirect innovation factor.

After World War II, VC in the US began to take advantage of the huge technology advances that emerged during the war. VC grew to $3 billion in annual investments by 1990, and then—as a direct result of the IT boom that it helped finance—to $30 billion in 1999.[26] By 2000, there were some 5,000 VC firms and entities in the US. In 2021, early-stage venture deal activity exceeded $80 billion.[27]

VC is a US creation—the sector was invented in the US, and no other country yet has evolved a VC sector that rivals it. The sector's origins are intriguing. In 1946, Georges Doriot—a French-born professor at the Harvard Business School who had served as an American general during World War II working on R&D and economic recovery activities as the Allied armies moved through Europe—founded one of the first VC firms. He developed his principles of entrepreneurship and VC in the 1940s and 1950s and centered his activities in the Boston area, with its nascent postwar high-technology sector.

Historically, the East Coast VC model focused on financial engineering, with less emphasis on a start-up firm's longer-term success than on its tax benefits and shorter-term returns. The East Coast VC sector's biggest initial success was in the Route 128 corridor of tech firms just outside of Boston, including Digital Equipment Corporation (DEC).

A different West Coast VC model grew up in California. Driven more by science and technology, the interest was in longer-term innovation results. It sought out technology-based innovative start-ups and entrepreneurs in northern California and invested in them, helping to build that dynamic entrepreneurial culture. Its biggest success has been through the firms on Sand Hill Road in Silicon Valley, and its model subsequently spread up and down the West Coast.

Because of the problem that established firms often have in undertaking radical innovation, VC filled a critical gap in funding entrepreneurs and start-ups to help bring on the IT-based growth of the 1990s, as well as the subsequent creation of biotech and software firms. The ability to bring out small, innovative firms became a significant competitive advantage for the US innovation system during this period.

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The two models have increasingly merged, and the VC investment model itself has evolved. Udayan Gupta notes that in earlier days, VC firms were built around taking equity or equity and debt positions in entrepreneurial firms, obtaining a return when the firm undertook an initial public offering or was acquired by another firm.[28] While that approach still dominates, VC investment is no longer in technology development alone. On the East Coast in particular, later-stage development funding, buyouts, turnarounds, rollups, and consolidations supplement earlier-stage financing. In addition, VC firms are no longer the only actors in preproduction-stage technology investment. VC funds, so-called angel investors, corporate venture funds, and even foundation and university endowments are now participants.

Gupta argues that the future of VC will remain anchored in technology development because of "the scalable nature of technology"—its ability to defy conventional financial analysis through multiplying returns. More flexible VC will fund technology innovation because innovation is time-intensive, not capital-intensive; and capital can't substitute for time in the creation of sustainable firms.

Despite all of VC's success with US innovation, however, it has its limits: VC firms will not fund research or early-stage technology development (ESTD), except in the biotech sector, and generally will fund only technology that is no more than two or three years from production. This development gap remains a major problem for the US innovation system: VC is a significant indirect innovation factor, key to the growth of technology-based firms, but it supports a postresearch seedling stage but not longer-term technology scale-up.

A good test for an indirect innovation factor is whether it can wreck an innovation system if it goes badly awry. The good news is that while both play a significant role in innovation and each has its own set of problems, neither accounting standards nor VC is a "wrecker." That is because indirect innovation factors don't directly create innovation. Still, they are part of the complex innovation system and cannot be ignored.

THE DEBATE ON THE GOVERNMENT'S INDUSTRIAL INNOVATION ROLE

The federal government's indirect innovation role is widely accepted—there is little debate over the government's central role in fiscal policy, trade policy, and export controls, for example. In addition, the federal role in the three direct innovation factors—early-stage R&D, the talent base behind R&D, and innovation organization—is also understood and accepted. Where debate *has* raged for decades, however, is whether there should be a federal role in direct, industry-relevant, applied research and technology development.

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There is a deep irony in this debate. As is discussed in more detail later in this book, the DOD, pursuing its national security mission, has been a major funder of industry R&D for decades. Federal support for health research, which now totals more than $45 billion a year, and healthcare for the elderly and poor has led to industrial policy approaches in that sector as well, also reviewed later. Agriculture, energy, and transportation are other sectors with a history of federal industrial policy interventions.

This question of the federal role is important to this book. Let's take a brief snapshot of one period of the debate, beginning when it broke out in a major way in the 1980s. At the time, concern was growing that the US was "deindustrializing"—that the manufacturing share of national output was waning and that essential US heavy industry was in decline. There was further concern that the country was not at the cutting edge of implementing technology advances. Specifically, US markets were not directing investment capital to critical areas of the economy, and promising new firms were unable to secure start-up capital.

A US industrial policy was proposed as a response to counter these ills; it adopted some of what Japan was implementing. Japan had governmental policies to promote strong industrial growth; it identified winners in world market competition; and it promoted their growth through the country's Ministry of International Trade and Industry (MITI), moving, for example, to dominate world auto markets and computer chips.

One of the approaches advocated in the early 1980s was to establish a federal industrial development bank, with business, labor, and government represented on its board. A throwback to the New Deal's National Recovery Administration, it would pick and provide capital support for winners by identifying and supporting cutting-edge industries with potential for high growth and high-value employment. In parallel, it would support so-called losers by lending funds to rehabilitate major failing industries deemed important to the national economy. Barriers against imports, special tax breaks, subsidized loans, favorable regulatory treatment, and labor-management reforms (ending featherbedding labor rules that employ more workers than needed, as well as wage restraints, in return for management improvements) were also part of this agenda.

The economist Charles Schultze argued against this interventionist agenda, becoming a major voice in the debate. He had been budget director during President Lyndon Johnson's administration and chairman of President Jimmy Carter's Council of Economic Advisors. His basic contention was that the manufacturing percentage of the US economy was actually quite stable compared to Japan's, and it was broad fiscal and macroeconomic policies, not its government-run industrial policy, that were fundamental to Japan's success.

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Schultze wrote a classic attack on industrial policy, from which the comments here are drawn.[29] It appeared in 1983 at the height of the US concerns over both the Japanese and German challenge to US competitiveness. Mainstream economists strongly shared his views.

Japan's remarkable economic success in the 1970s and 1980s, Schultze argued, was founded on the government's encouragement of large private savings through tax laws, and also on its stimulative monetary policies sustained by its large budget surpluses at the time. Although Japan protected a large part of its home market against import competition, one key to the country's success was vigorous firms prepared to take risks in pursuing exports. Japan's industrial policies provided tens of billions of dollars in direct investment, subsidized loans, and loan guarantees to industry, and they spread this among a wide range of firms and industries rather than on a handful of preselected winners. Japan's Development Bank lent more than three-quarters of its funds to traditional infrastructure firms, utilities, shipping, and urban developers, not to technology winners.

While Schultze acknowledged that MITI did support auto and memory chip market penetration, he also noted that its approach had its list of failures. These included its failed attempts to enter the aerospace sector and to consolidate Japanese auto manufacturers into a "Big 3" and cut back other producers (Honda and Subaru refused to go along with the plan). In contrast to the image presented by US industrial policy advocates, Schultze viewed Japan's industrial policy as limited—indeed, minor compared to the role of the country's macroeconomic policies—and as quite different than the model then being discussed in the US of an industrial development bank and related policies.

At the center of the entire debate was the belief of some that US deindustrialization was real. Schultze didn't see it, but in retrospect, this clearly was the case. Also central was the question of MITI's role in Japan's ascendancy in and eventual leadership of the auto and electronic sectors. MITI was certainly an important part of that evolving story, but was it decisive?

Schultze also argued that the US Congress and executive branches were incapable of selecting a winning industrial structure effectively. The American political system, with all its regional focus, could not efficiently choose among individual firms and regions for funding support. In the end, he felt that government should not attempt to intervene in areas where its political role would limit its effectiveness, and it should be careful about employing a politicized toolset to embark on what we would call a late-stage innovation role traditionally played by industry. His review of the importance of Japan's macroeconomic policies emphasized the importance of the public sector's traditional indirect innovation role. In other words, Schultze wasn't arguing that the government should play *no* role; rather, he was focusing on what the appropriate role was, emphasizing

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indirect innovation factors. His warning about the inevitable politicization of government investments controlled by Congress and the executive branch is useful in dealing with the delicate area of innovation.

Some economists began to push back against a strict, anti-intervention position. For comparison, let's revisit Richard Nelson's more nuanced views on government support for high-tech innovation.

Nelson, who wrote a decade after Schultze, saw the onset of an era in which high-technology advancement, supported by governmental R&D (largely through the DOD) and a later-stage development role, was important to high wages, high-level skills, and top competitive ability. He noted, therefore, that creating systematic technological advances in a variety of fields was a reasonable innovation system goal and found that appropriate active government support could help generate competitive advantage in technology sectors, with the advantage, if industry-led, of being comparatively low cost. Technology advances, he concluded, could be building blocks for an economy's upstream and downstream industries, and in the particular technology sector itself.

Nelson had the advantage over Schultze of a decade of hindsight. Nonetheless, Schultze's warnings about government's tendency to politicize technology if involved at the industry stage present significant worries, and sound program design at the governmental level in this area is both vital and difficult to achieve. But it should be added that despite Schultze's concerns about politicization, in both defense and health—the two major government mission areas where the government has collaborated with industry on innovation in advanced technologies—that problem has been largely avoided.

By 2020, the tide on this debate had begun to turn. The former British minister of science and innovation Lord David Sainsbury wrote a noteworthy book attacking the mainstream neoclassical economic consensus for its failure to grasp the elements of advanced technology development.[30] A businessman and industrialist by background, not an economist, and also a former chancellor of Cambridge University, he wasn't afraid to take on the academicians.

Sainsbury noted a historic shift that informs his view: the dramatic rise of leading Asian economies. From 1820, when the Industrial Revolution in the West became large scale, until 1990, the economies of the G7 leading developed nations (the US, Germany, Japan, Britain, France, Canada, and Italy) grew from 20 percent of global gross domestic product (GDP) to 66 percent. But by 2020, that share fell back to 50 percent, its 1917 level. Meanwhile, a group of six industrializing nations—China, South Korea, India, Poland, Indonesia, and Thailand—experienced accelerating economic growth and productivity. There have been many pluses with this development, particularly a drop in the percentage of the world's population living in poverty.

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How did several Asian nations find a way to create competitive advantage in the world economy? The dominant economic theory of the G7, neoclassical economics, has now accepted innovation as the dominant factor in growth. But Sainsbury argues that having made innovation exogenous to economic analysis, it lacks an explanation for this Asian surge.

Sainsbury makes a neat division of fundamental economic movements in presenting his arguments. He says there is a "market efficiency" school, which could be seen as being composed of the eighteenth-century French physiocrat economists, Adam Smith, David Ricardo, Alfred Marshall, Paul Samuelson, and Paul Krugman. On the other side is a "production capability" school, which could be seen as composed of Alexander Hamilton, Friedrich List, the German Historical School, and Joseph Schumpeter.

The market efficiency school sees the origin of wealth in land, physical labor, and capital; the production capability school says that it derives from innovation and creativity in changing the stock of knowledge and tools. The analytical focus of the schools is also different. The market efficiency school focuses on markets and people as market traders, while the production capability school's focus is on production and people as innovative producers. Further, all market activities are qualitatively alike and subject to mathematical modeling according to the market efficiency school, whereas the production capability school argues that observable facts and experience are the basis for economic theories, tending to use biological analogies rather than the market efficiency school's mathematical and physics analogies.

Sainsbury further argues that the two schools have different foundational economic views. The market efficiency group has argued for avoiding interference in the marketplace, and that nations reach an equilibrium state amid recurring business cycles. As Paul Krugman put it, "Global weather is a self-organizing system; so, surely, is the global economy."[31] In contrast, the production capability group sees the potential of a dynamic state, not an equilibrium state, with the opportunity for continuous progress through expanding human knowledge.

Underlying these differences are differing views of human nature. The market efficiency school sees a human propensity toward barter, trading, and exchange of goods and money. In contrast, the production capability school sees a human tendency to improve workmanship.

The Cold War submerged the debate in the West into a struggle of competing economic ideologies, where absolutes prevailed. While Hamilton's model for the then-underdeveloped US resembled the East Asian model of today, with its emphasis on industrial technology and commercial development, this perspective got lost when communism's emphasis on government control pushed a Western reaction toward its

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opposite (namely, Adam Smith and laissez-faire economics). Of course, some kept production capability ideas alive, as through Richard Nelson's emphasis on innovation systems.

In effect, Sainsbury is arguing that Robert Solow, with his concept of "technical change," picked up the core idea of the production capability school and placed it above the classical economics ideals of capital and labor. But when he found it exogenous, it became residual, lost on the cutting-room floor, because it had to be outside the neoclassical world of markets and mathematical modeling. In other words, Solow didn't go far enough; he didn't use his innovation-based growth theory to blow up neoclassical modeling. While Paul Romer attempted to make growth endogenous, his is an unfinished revolution. Sainsbury argues, from his perspective as a former leading policymaker, that neoclassical economics is of limited use to policymakers who want to pursue growth and corresponding economic well-being. In technical terms, neoclassical economics doesn't adequately explain total factor productivity, the measure of productive efficiency, which is at the core of growth.

While neoclassical economics assumes a market economy with perfect competition, with each firm selling the same product at the same price, Sainsbury's emphasis on a "dynamic capability"[32] theory of growth perceives that firms compete by trying to gain competitive advantage with product improvements and new products. A nation's standard of living depends on the capability of its firms to obtain a high level of value added per capita in the industries where they compete. To get there, they can increase production efficiency by innovating, and create competitive advantage based on a combined capabilities/market opportunities dynamic—that is, they can grow their dynamic capabilities and apply them to market opportunities. Firms must build capability, identify a "window of opportunity," and then use organizational and technological capability to take advantage of it.

Sainsbury goes on to argue that there are four elements that empirical studies indicate are critical to growth:

- *Demand* for specific products or services (which can be latent demand, such as Steve Jobs pursued in producing Apple's Macintosh computer)
- *Activity-specific technology* to produce products or services, which, combined with product/service demand, create a new "window of opportunity"
- *Capability of a firm*, which governs the ability to apply activity-specific technology to producing a product or service to meet demand, and which in turn works in a capability/market opportunity dynamic
- *Institutions* that operate in a national economy to enable the capability/market opportunity dynamic

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The government fits into the last of these elements. Sainsbury says that the government role should not be pervasive but rather supportive, and it can play an active and critical role in fostering and enhancing the dynamic capabilities of firms. Sector-specific strategies are required, and some sectors will be more productive than others because what he calls the "windows of opportunity" will be unevenly distributed among various sectors and industries. The firm role is critical, but the government role provides vital support through a range of policy approaches.

Sainsbury brings a dose of industry realism to our exploration of the role of innovation in economic growth through his focus on the dynamic capability of firms. He is further refining Nelson's focus on innovation systems by taking a closer look at the role of firms. The translation here of both Nelson's and Sainsbury's ideas results in the concept of innovation organization as a third direct innovation factor, joining the R&D and talent factors supplied by Solow and Romer.

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3 THE ORIGINS OF AMERICAN INNOVATION ORGANIZATION

Where do American research and development (R&D) organizations come from? What is the political ideology that governs them? How do they think and act? How are they organized? What is their rule set? We discussed in the preceding chapters that technological innovation drives growth and performing R&D is a direct factor in technological advancement, as is the organization of innovation into a system. Given the central role that government plays in earlier stages, how has this R&D innovation organization been approached at the federal level in the US?

THE IDEOLOGY BEHIND FEDERAL RESEARCH AND DEVELOPMENT

To understand US innovation, we need to understand the political ideology behind it. David Hart[1] has argued that there are five underlying ideological approaches to the governance of technological innovation that evolved in the 1920s and 1930s in the US and remain with us today.

First, an ideology of *conservatism* toward R&D organization evolved in the 1920s as a reaction to what many viewed as the excesses of President Woodrow Wilson's mobilization for World War I. In that period, government took control of much of the industrial economy, setting prices and dictating production. The conservatism movement recognized a need for the state to provide for the national defense, including technological innovation for the military, but it believed that the government should otherwise stay out of R&D territory. One of its goals was to keep the military R&D sphere isolated from the domestic economy.

Frank Jewett was a major exponent of this direction. A highly respected engineer and technology organizer, he headed Bell Labs from 1925 to 1940 and was president

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of the National Academy of Sciences from 1939 to 1947. Leading the most important private-sector lab may account for his desire to limit federal R&D competition. He felt that federal meddling with R&D would slow the growth of science advancement—although he did acknowledge the need for defense R&D. During World War II, he supported the growth of federal R&D, but after the war, he supported its retrenchment.

Hart identifies what he calls *associationalism* as a second ideology; it evolved into the concept of "public-private partnerships" in recent decades, espoused by Presidents Bill Clinton, George W. Bush, and Barack Obama. The ideology originated in the World War I mobilization. Herbert Hoover was a leading exponent; he was US commerce secretary from 1921 to 1928 and then US president for a single term. As an engineer involved in mobilizing large relief projects, he saw the power of state action and believed that unlimited economic competition prevented firms from taking the risk of investing in innovation. Competition, he felt, limited needed large-scale R&D, fragmenting industry attempts at innovation. The government's role was to disseminate best practices to rationalize industry, including by fostering industrywide R&D facilities run by trade associations backed by the government and through government-supported service facilities that supported industry R&D. Hoover wanted close ties between industry R&D managers and bench scientists in the context of government-industry cooperation with pooled resources in order to avoid duplication.

Hoover brought this view to the Commerce Department and its Bureau of Standards, expanding the bureau's laboratories to embrace an R&D support role; eventually, as its technology role grew, it became the National Institute for Standards and Technology (NIST). Hoover's aims included reorganizing "sick" industries with new technology advances, building collaborative industry R&D, and removing barriers that limited high-growth industries.[2] His successor in the White House, Franklin D. Roosevelt, picked up Hoover's associationalist ideas and built much of his National Recovery Administration on them as part of the New Deal.

Hart's third ideology is *reform liberalism*, a return in some ways to the "trust-busting" concepts of President Theodore Roosevelt. After the US Supreme Court declared the National Recovery Administration unconstitutional in 1935, antitrust thinkers such as Attorney General Robert Jackson (later one of the Supreme Court's associate justices) argued that cartels and industrial collusion suppressed innovation because they could disrupt innovators through their market dominance. The basic theory was to reestablish competitive markets and the entry of competitive innovators through government regulation and antitrust enforcement. The movement saw government as an economic actor, able to break bottlenecks that held back innovation or develop new technology itself to spur competition.

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This movement was largely displaced by World War II mobilization, which led to more joint government-industry associationalist efforts. Following World War II, government emphasis shifted toward an effort to grow the federal R&D role through university research, building on wartime developments.

That shift—which Hart calls *Keynesianism*, the fourth ideology—emerged in the 1940s, adopting John Maynard Keynes's economic theories of the government role. Its view was that government spending could contribute liquidity to private markets to spur demand. The movement saw widespread market failure in the inability of the private sector to manage the risk of breakthrough R&D, and it believed that government should offset that gap with federal R&D investment.

Keynesians argue that aggregate R&D spending by the federal government is a critical measure of the adequacy of R&D investment in the economy. For example, the biannual *Science and Engineering Indicators* report from the National Science Foundation (NSF) is the leading way that we track these economic signals; this report was cited extensively in chapter 1.

Last but not least, there is Hart's *national security* concept, which emerged during World War II and was picked up again in the long Cold War that followed. The essence of this ideology is that the nation should use any means and any necessary model to create the science and technology leadership required for national defense.

During World War II, the ideologies of associationalism and national security effectively merged in an approach led by Vannevar Bush, Roosevelt's wartime science advisor. The approach was curtailed at war's end but revived during the Cold War—but with a twist.

The Cold War opponent of the US, the Soviet Union, was communist, so it controlled all its economic activity. In an ideological reaction to its opponent's state control, US R&D policy became bipolar, advocating market mechanisms and denying a federal role in the private sector, but embracing federal intervention for defense. We shall see how this evolved as the chapter goes on, but the point here is that national security proponents believed that the federal government should be highly interventionist in the economy where defense needs arose. This intervention led to major advances in electronics, aerospace, and computing.

All five of the ideologies that Hart identified still get advanced in technology debates. When I served as a senior advisor in the US Senate for more than fifteen years in the 1990s and 2000s, I found that all of them were still alive and well. They often came to the forefront when technology policies were being debated on the Senate floor, with different senators espousing different perspectives. For example, I recall Senator John McCain (R-AZ), a leader of the Armed Services Committee, praising the work of In-Q-Tel,

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an intelligence technology agency with the authority to take equity positions in companies to spur intelligence-related technology advances. That was a classic national security ideology perspective—the government could even take an ownership position in tech firms to obtain technologies for national security.

I recall McCain, whom I highly respected, joining other Republicans in opposing NIST's Advanced Technology Program (ATP) as "picking technology winners and losers" in an untoward government intervention into private-sector company competition. That was a classic conservatism perspective.

Today, what we often encounter is a hybrid ideology, a blend of the different visions of the state role, with underlying conflicts between the positions unresolved. A kind of pragmatic blur, as occurs so often in politics, has tended to prevail. National security and associationalist are more dominant than the others currently, the former having been diminished by the end of the Cold War and emerging again, strongly, with the rise of China as a symmetric technology competitor. This has tended to reduce the influence of the conservatism ideology, although it still has its moments.

Competition with China has also led to a growing associationalist perspective, with public-private partnership a strong theme, particularly of recent Democratic administrations and now more shared across political lines. The reform liberalism view faded in the 1980s and 1990s, when intense international competition between firms limited antitrust concerns, but the rise of tech giants such as Google, Amazon, Facebook, and Apple in the 2000s resuscitated the ideology, with politicians of both parties now calling for regulatory curbs on these massive firms. Meanwhile, Keynesianism-type concerns about aggregate investments in R&D keep chugging along.

Why is classifying the debate over R&D and technology policy into categories important? Since the federal government is a major actor in innovation organization, these ideologies will determine what the government will be willing to undertake and what it won't, with each step requiring a policy justification in the executive branch and Congress. These perspectives will also help guide our understanding as we discuss how US innovation organization has evolved.

ALFRED LEE LOOMIS AND THE GROWTH OF THE FEDERAL R&D ROLE

Alfred Lee Loomis, largely unheralded, deserves credit as a founder of a new system for organizing American R&D.[3] In a life of tremendous accomplishments, that is his most important and enduring one. How he got there is a fascinating saga.

As the son of a prominent New York heart doctor, his interest in a science career was thwarted when his father had an affair with an infamous beauty and his mother sued

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for divorce, causing a great society scandal. His father then died while Loomis was in college at Yale, studying math and science. To support his mother and family, he went to law school and then practiced in a prominent New York law firm.

An Army officer in World War I, he worked on ballistics research projects at the Aberdeen Proving Grounds in Maryland, inventing the Aberdeen chronograph for measuring muzzle velocities. The experience taught him the limits of applied science within the military's hierarchical bureaucracy. He dropped law after the war and turned to building an investment banking house. He studied electric power systems and then financed a network of new utility firms in East Coast states, pioneering the concept of the utility holding company as the US electrified at scale. He made one of the great postwar fortunes and then, presciently, cashed in all his holdings for gold at the top of the market in 1928.

A yachtsman and a charismatic figure with movie star looks, he may have seemed an unlikely candidate for a science leader. But as Wall Street crashed in the Great Depression, Loomis turned back to science, converting a massive, Tudor-style mansion in Tuxedo Park, a gated enclave of the rich sixty miles north of Manhattan, into perhaps the most important private science laboratory in the US in the 1930s—Tower House. It boasted the most advanced scientific equipment, which few universities could afford, and its reputation quickly spread.

Loomis sponsored the "summer study" program and brought the world's most prominent physicists to study and experiment there, including Albert Einstein, Werner Heisenberg, Niels Bohr, James Franck, and Enrico Fermi. In addition, he undertook his own extensive research on ultrasonics and microwave physics, authoring twenty-nine articles in the 1930s. In biology, he pioneered techniques for electroencephalography and discovered the sleep K-complex brain wave. He worked with many of the scientists who came to his Tower House lab, earning a reputation for his capabilities and energy. Loomis won the Franklin Institute's Wetherill Medal for developing the microscope centrifuge in 1934.

As another world war menaced, the Loomis research team turned to radio waves, building an early microwave radar. Both Britain and the US had developed long-wave radar between the wars, and the US tested early sets against the maritime traffic coming down the Anacostia River from Prince Georges, Maryland, to Washington, D.C.

The British, facing air attack from nearby Germany's massive Luftwaffe, were desperate to develop an air defense system. Henry Tizard, a World War I test pilot, chemistry professor, and rector of Imperial College London, led a Royal Air Force (RAF) science committee and an effort to develop long-wave radar systems that led to the Chain Home system of radar screens on poles along the coast, linked to a radio communications center and in turn connected to RAF fighter bases and planes. The system helped

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enable Britain's much smaller air force to take on and reverse Germany's air assault and save Britain—the fighters could scramble into the air and attack from above just as the bombers approached. Tizard also promoted the development of microwave radar that was small enough to place in aircraft to enable night flying and much more effective antiaircraft shells and ship and aircraft identification.

By 1940, a team of scientists working for the RAF and led by John Randall and Harry Boot had developed a "cavity magnetron," a device that could emit hundreds of watts at a 10-centimeter wavelength—1,000 times more powerful than the best American transmitter. It was potentially war-winning technology, but it needed extensive additional development.

At the dawn of World War II, Loomis became the unofficial science advisor to his cousin, Henry Stimson, who was Franklin D. Roosevelt's noted secretary of war. He also served with Roosevelt's science advisor, Vannevar Bush, on his National Research and Development Committee (NRDC), later subsumed under Bush's Office of Scientific Research and Development (OSRD), which organized wartime science and technology development. Bush's committees were not science labs; they supported science at other organizations.

In 1940, during the Battle of Britain, Winston Churchill dispatched a scientific team to Washington, led by Henry Tizard, to attempt to trade military technology secrets with the US military. The British had the cavity magnetron, the gas turbine for jet aircraft engines, and advances toward nuclear weapons. On the American side, the British were interested in the Norden bombsight for precision bombing.

Loomis, who knew many British scientists, hosted a dinner in Washington for the Tizard mission when it arrived. The outlook for Britain looked dark; the American generals and admirals whom Loomis had convened assumed that Britain was going to lose the war, so they had no interest in sharing military secrets. Desperate, the British scientists began hinting at their progress on microwave radar. Loomis, who was probably the leading microwave physicist in the US at the time and had been working on his own microwave radar, was the only one in the room to get the hints.

After the miserable meal, Loomis gathered Tizard and the British scientists in his apartment. Frank discussions began, and the British shared their radar secrets. Loomis invited the delegation to Tuxedo Park, where they demonstrated their cavity magnetron—one of only twelve sets in existence and the world's greatest military secret in 1940—and gave it to him.

Loomis was uniquely positioned to understand the importance of this new technology, and he immediately swung into action. He telephoned his good friend Ernest Lawrence, the leading physicist in the US, whose cyclotron research Loomis had supported,

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and asked him to fly to Washington right away to meet with him. He spoke to his cousin, the secretary of war, and told him that a major crash project was needed to begin right then to develop a new kind of radar. Stimson alerted George C. Marshall, the Army chief of staff, and obtained immediate approval from President Roosevelt.

In his capacity as chair, Loomis convened the NRDC microwave committee to discuss implementation. He was joined by Vannevar Bush, the Harvard University president James Conant, the Massachusetts Institute of Technology (MIT) president Carl Compton, and Frank Jewett, the president of Bell Labs—which is where Jewett proposed the project be located. For his part, Loomis proposed that it be located outside of industry, at MIT, and with his reputation as a leading industrial organizer, he won a 4–1 vote to put it adjacent to the MIT campus on an unused industrial site.

Loomis and Lawrence next began contacting a "who's who" list of American scientists. They were asking the scientists to leave their academic jobs and show up in Cambridge, Massachusetts, in two weeks for a critical wartime project, but they told them that they couldn't discuss the secret technology on the telephone. Their prestige was so great, however, that nearly all the scientists agreed. That October, the Radiation Laboratory (Rad Lab) at MIT—a cover name to allay suspicion that it was anything more that basic academic research on the then-obscure topic of nuclear radiation—was created in Cambridge under Loomis. A branch was also set up in Britain.

When the Rad Lab opened, Loomis closed his Tuxedo Park lab and shifted key staff to Cambridge. The lab went on to develop microwave radar as a critical and pervasive military technology for the Allies in the war. Loomis himself also did some inventing there, notably of the long-range navigation (LORAN) system used by aircraft and ships until the global positioning system (GPS) was developed. He also made major advances toward developing the system for ground-controlled aircraft landing.

The day after seeing the cavity magnetron at work, Loomis began to work out the basics of a major new centralized applied microwave laboratory. Its scientists would be civilians—both Loomis and Vannevar Bush had seen in their World War I experiences the perils of subjecting science to the military bureaucracy. Loomis also knew the value of technology leadership: the idea that the boat in front gets the new breeze first, just because it is ahead, and thereby increases its lead was a maxim from his yachting experience. So he had exchanges with Tizard and his group and drew on the models that the British had used to engage civilian scientists in developing long-range and microwave radar, protected as a team outside military control and with the resources to undertake a crash development project.

Quickly, Loomis established the new Rad Lab's three major technology projects: airborne interception, gun-laying for antiaircraft weapons, and LORAN. He arranged

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funding for development of the cavity magnetron within days of seeing it operate, personally financing it until federal money was allocated. By October, the finest physics experts in the nation were joining the new Rad Lab.

Loomis implemented many of the best practices, which show up again and again at the best R&D organizations:

• *Great talent*: Loomis and Lawrence recruited leading experts in the field. Ten Nobel prizes eventually went to Rad Lab scientists, and much of that award-winning work came out of the lab's experiments and advances.

• *Flexible funding*: As noted, Loomis advanced his own funds to start the lab since military procurement wasn't yet used to funding major projects overnight. To further speed this along, much of the contracting with industry for development was nonbid; Loomis just made the awards because there was a war on.

• *A flexible, nonhierarchical organizational model*: The Rad Lab was a flat, nonbureaucratic organization focused on flexible, interacting groups and teams. Leadership was based solely on talent. It was purposely kept apart from military bureaucracy and out of uniform. There was easy camaraderie, high spirits, a casual tone, and close interaction between teams. Everyone accepted long hours and intense work because they understood and were committed to the mission. The staff at the outset, consisted of thirty-six scientists and one secretary. Although the Rad Lab had grown to several thousand by the end of the war, it remained committed to a flexible, team-based structure.

• *An ability of lab leadership to rise to the top*: Loomis chaired the Microwave Committee, which sat above the Rad Lab in the hierarchy, and he reported officially to Bush, chair of the NDRC and then the OSRD. Bush had direct ties to President Roosevelt and his top aide, Harry Hopkins, and Loomis had a close working relationship with Secretary of War Stimson and often went to him directly to get things done. This access forced an often slow-moving military bureaucracy to adopt the new technology, and the key decision-makers were critical to the lab's success.

• *The technology challenge model:* The lab was designed to meet specific technology challenges based on fundamental breakthroughs, and it was connected to development, prototyping, and what amounted to an initial product market. It was closely connected to industry, with which it collaborated constantly on the development phases, and worked closely with military operators to assure that the technologies that it evolved were functional and met real needs. It thus pioneered the elements of the technology challenge model at the federal level.

By the end of the war, the Rad Lab had moved from fundamental science breakthroughs around microwave radar to 3-centimeter radar, the LORAN system, gun-laying

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radar, radar beacons for identification of "friend or foe," development of transponders, ground-control approach radar, and large-area interception radar. Advances from the Rad Lab, for example, enabled Britain to shoot down more than 80 percent of the V1 rockets that the Nazis launched in their attempt to destroy London.

Loomis went on to play a crucial role supporting the atomic bomb project. Roosevelt had set up a Uranium Committee after Albert Einstein wrote to him in August 1939 warning about the imminence of atomic weapons, but it was viewed as a long-term research project to be realized after the war. Through his association with Lawrence and other leading physicists, Loomis believed otherwise, and he worried about German advances under Werner Heisenberg—someone he knew from Tuxedo Park. Loomis persuaded Stimson to accelerate the Uranium Committee dramatically into the Manhattan Project, which Roosevelt immediately approved.

The Manhattan Project was set up along the exact same lines as the Rad Lab. Eleven of the most able Rad Lab physicists, including subsequent Nobel winners Luis Alvarez and I. I. Rabi, went to Los Alamos, New Mexico, at the outset, bringing the model with them to J. Robert Oppenheimer, the wartime head of the lab there, who applied it.

The model was so successful that it kept spreading. Its rule set became the essence of the Federally Funded Research and Development Center (FFRDC) model that has dominated US energy, defense, and other federal labs ever since. Bush had set up his NRDC and OSRD committees to contract out for research advances, creating or using institutional labs and resources for the actual R&D, which became initially known as Federal Contract Research Centers.[4] But the Rad Lab was the first, and its success meant its organizational system became the model for the many follow-on FFRDCs.

Loomis shared the conservatism and national security ideological outlooks described earlier for the federal research role: government R&D was for defense needs, and with the end of the war, the defense justification ended. So, promptly after the war, he and Vannevar Bush moved to dismantle the Rad Lab. Its staff prepared a remarkable twenty-seven-volume summary of its technical accomplishments,[5] which became the basis for much of the advance in American electronics after the war.

By 1947, the Rad Lab was closed, but as the Cold War picked up, it was effectively reestablished as the noted Lincoln Lab at MIT, which remains the leading military center for radar technology, among other advances. Loomis, who always sought privacy and avoided the limelight, withdrew from public life after a scandalous divorce, dying—almost unnoticed—in 1975.

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VANNEVAR BUSH AND THE PIPELINE MODEL

While Loomis gets much of the credit for establishing the FFRDC model for federal lab R&D, Vannevar Bush, his wartime partner and Roosevelt's World War II science advisor, formed much of the model for the overall system that took hold after the war. Bush was a remarkable talent: a former dean of engineering and vice president at MIT and then head of the Carnegie Institution for Science in Washington before advising Roosevelt. He is considered a leading computer science theorist, having developed the "differential analyzer," a room-size array of rods that could be turned and set—*programmed*—to solve differential equations. He also knew industry and was a founder of Raytheon. In the 1930s, he led the National Advisory Committee for Aeronautics (NACA), the predecessor of the National Aeronautics and Space Administration (NASA), which organized aviation R&D between the wars and helped prepare him for his role during World War II, when he became the nation's most recognized science leader and even appeared on the cover of *Time* magazine.

As an Allied victory in World War II was becoming clear, Roosevelt and Bush began to consider the postwar policies for the remarkable science establishment that had been built in the US during the war. Roosevelt wrote an open letter to Bush on November 17, 1944 (likely drafted by Bush himself), which raised four questions about science's future: How should the science knowledge gained from the war be diffused into the economy and society? How could a "war of science against disease" be organized? What should the government's role be in supporting public and private research, and in developing science talent?[6]

Bush's July 1945 response to the letter became the most influential policy paper ever on US science organization. Roosevelt had died that April, so the letter went to his successor, Harry Truman. Called "Science, the Endless Frontier,"[7] the paper's title drew on the historian Frederick Jackson Turner's concept, expounded in 1893, of the dynamic role of the American frontier in creating a democratic society.[8] While the American frontier was legally closed in 1900, Bush argued that science could constitute the nation's next frontier—and this frontier of the mind would not close, but rather—as his paper's title stated explicitly—would be endless.

The Bush paper was not a typical academic work; it was a polemic that advocated new directions for US science. In it, he aimed to define the future direction of US science progress, organizing it around popular causes. Science was to be a separate player from other parts of the innovation system; he did not support an integrated model for science.

There were four goals. First, there was to be a war against disease. Bush and Roosevelt had seen the huge medical gains made as part of dealing with the casualties of the

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war. Antibiotics, introduced through a systematic government effort, sharply reduced the rate of death from disease in soldiers, once the leading cause of death in wars for combatants, to a fraction of what it had been in World War I. Many other disease areas were tackled as well, including displacing pneumonia from its long role as the leading overall cause of death. Bush saw the antibiotic effort as a model, believing that a greater government focus on science could address many diseases.

The second thrust in Bush's list justifying federal research investment was national security. This was not a hard sell to the American public; everyone had seen how science and technology transformed war, from radar and electronics to atomic weapons. Bush argued that keeping up peacetime defense research would be vital to continuing US security, and a lesson from American lack of preparedness for World War II was not to rely solely on allies for science. Bush insisted, too, that a Rad Lab approach of keeping science out of uniform and having civilian leadership of research would be important.

Bush called a third goal "public welfare." In the immediate postwar period, there was great anxiety that the war machine's massive employment was being rapidly shut down and the 16 million returning veterans would have no jobs. In short, there could be another major depression. Full employment to address this anxiety became a major public goal, and Bush argued that the backlog of technology advances from the war and continuing investment in research would play a critical role in meeting that goal. Basic research was public capital, he argued. Invest in research and we'll have jobs.

The fourth goal was for the federal government to nurture science talent. Without a strong talent base, science progress would be limited. Bush's arguments paralleled Robert Solow's and Paul Romer's subsequent theories about the need for strong R&D investment to fuel economic growth and the need for "human capital engaged in research." The case that Bush made had political appeal: if taxpayers invest in research, it will yield a war against disease, support national security, and increase jobs; investing in science education will be a critical enabler.

Bush had what is called a pipeline theory of innovation. The federal role was to fund basic, not applied, research, and to leave to industry the follow-on role of applying that research to practical problems. The government should increase scientific capital by supporting academic research, which was to be removed from "pressure for immediate, tangible results." Science was to be removed from the fray, going back into the ivory tower after the war. It was a sharply limited vision for science compared to the one that he had had in his World War II science advisor role, which involved overseeing a highly integrated system of research through development, reaching all the way to product production. His pipeline model ended his wartime approach, with its close collaboration between among industry, government, and university researchers. The federal

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government would dump basic research into one end of the innovation pipeline, mysterious things would occur, and great new technologies would emerge at the other end.

There would be gaps, as Bush recognized, so he proposed offering industry a federal tax deduction for R&D and called for patent system reforms. For industries outside the reach of science, the government should disseminate science advances. He noted, too, that applied science advances from the war should be made available to industry to support technology advances—the government should "lift the lid" on these advances for industry use. He wanted an opening of new frontiers, seeing this as a historical federal role. He extended the concept to justify a governmental science role, but it was a limited and controlled one. His called for a single foundation that would support his vision of basic research across all scientific fields.

Why did this remarkably talented and knowledgeable leader walk away from his World War II–era connected model for innovation and substitute what must be considered a "disconnected" model? Bush saw during the war how science had been drawn into the political system. He was a friend of Oppenheimer, who led the Manhattan Project in Los Alamos, and likely shared some of his concerns about how physics had been drawn into the atomic bomb project without full thought being given to the societal implications.

Perhaps most important, though, Bush knew that the federal support that had created a massive wartime science effort would be eliminated as peacetime approached, and he wanted to salvage key aspects of it. Basic research was the cheapest stage, far less costly than applied research, so perhaps that could be sustained. The federally funded research university had been created under Bush's purview during the war—MIT, for example, received eighty times more funding during four years of war than in all its previous eighty years of history. Bush certainly understood that retaining and continuing to build these research universities could be foundational. But his postwar design shattered the unity of his wartime design for science.

VANNEVAR BUSH VERSUS JOHN R. STEELMAN

Like all policy proposals, Bush's design met a number of political and practical challenges.[9] John R. Steelman, who had been a professor of sociology and economics at Alabama College before entering government service, was his most formidable opponent.[10]

Steelman was recruited in 1934 to the US Department of Labor's Conciliation Service and was later its director, becoming a key advisor to Frances Perkins, Roosevelt's secretary of labor. He later helped President Truman resolve economy-threatening disputes with coal miners and railroad labor. In 1946, Steelman became an assistant to Truman, a position that in later administrations evolved into the White House chief of staff.

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Congress passed Bush's original proposal for a foundation to oversee all of science research in 1947. But Bush's structure had scientists naming other scientists to its leadership, independent of presidential control. It appeared to Truman to violate the constitutional system for executive branch control.

Bush had enjoyed a strong working relationship with Roosevelt and his key aide, Harry Hopkins, but he didn't get along well with Truman. The new president was not fond of elites—he had grown up too poor to go to college but was very bright and had been a standout Army artillery officer in that math-oriented branch—and likely saw Bush as part of that group, although Bush's origins were in the lower middle class. Truman vetoed Bush's bill, not wanting the new science foundation and large budgets for science to operate outside of overall presidential management.

At Truman's behest, Steelman led a group of largely former New Dealers in producing a four-volume study of federal support for science—a much more comprehensive publication than Bush's paper. The Steelman report proposed much greater government involvement and funding for R&D, with far more emphasis on public funds for development as well as research. While Steelman placed the proposed funding agency under executive branch control, it was not to be the only actor; other federal agencies would fund development projects, in addition to research, that aligned with their missions. Rather than leave science on its own, as in Bush's laissez-faire approach, the report proposed central coordination for R&D agencies through the executive office of the president, links to industry, a doubling of US R&D funding in a decade to 1 percent of gross domestic product (GDP), percentage allocations of federal research funding to key policy areas, and systematic talent needs assessments. Bush opposed these associationalist features of the Steelman report and feared a stronger presidential role would politicize science.

As the Bush and Steelman designs collided, political forces demanded a resolution, in part because science had become an instrument of hegemony between the Cold War superpowers. The National Science Foundation (NSF) Act was finally passed in 1950, although the agency didn't receive significant funding until after the Soviet Union's launch of the Sputnik satellite in 1957.

The NSF had been the brainchild of Bush, but it never became the central hub of federal research that he had envisioned. The five-year delay in adopting the NSF meant that science efforts in the US would be decentralized, without a single science agency, but rather many. Other agencies popped up or expanded to fill the gap. The newly created Office of Naval Research took on much of the basic research support role; the Manhattan Project labs were retained and expanded under Atomic Energy Commission (AEC) purview; and the National Institute of Health became the growing National Institutes of Health (NIH). Steelman's more multiagency approach, with a modest-size NSF and other,

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more generously funded research agencies attached to mission-oriented departments, set the framework for the US federal research enterprise.

The Sputnik crisis in 1957 led the public, the media, and Congress to the conclusion that academic basic research might contribute to US Cold War success, and NSF funding was increased threefold. Truman's successor in the presidency, Dwight D. Eisenhower, implemented many of the Steelman-type recommendations, including a presidential science advisor and a science advisory council. But there was never one tent for science, as Bush had envisioned. To this day, despite the many advantages to decentralized science, there has been a continuing problem of science coherence in the US system.

While it may be that Steelman is more the actual architect of American science policy than Bush, one thing is certain: Bush's linear model of innovation has remained firmly entrenched in the minds of policymakers. Basic research became the core focus not only at NSF, but also at other federal civilian science agencies. The linear model's intuitive appeal—that innovation is produced like a car or a toaster, along a conveyor belt of sequential stages—may be why this model continues to inform the role of government in science.

THE OUTPUT FROM BUSH'S BASIC RESEARCH PIPELINE MODEL

Bush was frustrated, then, in his attempt to create one large tent sheltering all of science at NSF; the decentralized US science model meant that there were many tents. But he was successful, as noted, in promoting the federal science role as supporting basic research. Although it was an inherently disconnected approach, there have still been impressive gains from this model. The creation of the federally funded research universities that went with it has been a major enabler, and Bush deserves much credit for this.

The examples of federal research that led to technological advances are legion. Tracing technologies to their originating science is a lot like genealogy research before the internet—difficult. But Peter Singer has traced the origins of many key advances:[11] In the field of information technology (IT), these include the following:

- The Google search engine stemmed from NSF computer science grants.
- GPS had its origins in Navy research on atomic clocks and defense satellite research, as well as applied research at the Defense Advanced Research Projects Agency (DARPA).
- Supercomputing developed at the national energy labs.
- DARPA backed speech recognition software as well as the first internet, ARPANet, among other advances.
- NIST at the Commerce Department supported the development of closed captioning.

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- The technologies behind smartphones were advanced by research at the US Department of Defense (DOD) and the NSF, through grants from the federal Small Business Innovation Research program, and at other agencies.

In the field of energy technologies, they include the following:

- The national labs backed seismic imaging that led to the shale gas revolution.
- The development of light-emitting diodes (LEDs) was initially supported by US Air Force research funding.

In health, they include the following:

- Magnetic resonance imaging (MRI) was expanded from NIH-supported diffusion tensor imaging.
- The Veterans Administration and DARPA have backed advanced prosthetics.
- NIH sponsored the Human Genome Project, as well as advances in AIDS, with expedited approval processes from the US Food and Drug Administration (FDA).
- DARPA significantly boosted the messenger ribonucleic acid (mRNA) technologies behind the COVID-19 vaccines, with support coming later from NIH.

In mathematics, they include the following:

- The technique of reverse auctions was supported by the NSF, as was the kidney supply matching program.
- In the civil aviation field, the Army, Navy, and NACA supported a host of aeronautics advances.

In agriculture, they include the following:

- The sector has long benefited from science advances from federal research support at land-grant universities.
- Hybrid corn, which enabled a later food production revolution, was first explored at a Department of Agriculture research extension program.

DONALD STOKES AND THE CRITIQUE OF BUSH'S PIPELINE MODEL

As we have seen, World War II transformed the relationship between science and government. The prewar US had some federal science entities, such as the US Geological Service, the Naval Research Laboratory, a public health lab, and agriculture research at land grant universities and experiment stations. And it had nascent research universities built on the German university model. Vannevar Bush's government mechanism for wartime science, the OSRD, was as close to a unified science organization as the US has achieved.

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The war marked an unprecedented flow of funds into basic as well as applied research, particularly in the fields of physics and electronics.

Bush's new organizational model reflected Roosevelt's penchant for creating new programs outside the established government agencies. Bush and his core group of allies, including MIT president Karl Compton, Harvard president James Conant, and Alfred Loomis, saw how the war's outcome would be driven by science and technology and operated as Roosevelt's agents to achieve this, operating in close contact with Harry Hopkins, the president's chief aide. OSRD was part of Roosevelt's executive office of the president and contracted for science work while having no labs of its own, relying on leadership from the scientific elite.

Senator Harley Kilgore, a New Deal Democrat from West Virginia, had earlier introduced legislation for postwar science organization, and part of Bush's plan was in reaction to this Senate bill. Kilgore proposed a standard executive branch agency in which presidential appointees, not scientists, would have the controlling voice. Bush reversed this in his proposed agency. Bush's aim for what became the NSF, as discussed, was to have federal support of basic research, but also to limit the federal role in science. He wanted an entity with authority as broad as his OSRD across science. Its leadership would be chosen by a board of scientists not named by the president or controlled through the White House.

Bush's efforts to adapt the OSRD model to govern US science and fund basic research was greeted with acclamation from university scientists after the war, and he achieved near-sainthood as university science expanded in subsequent decades. It was not until 1997 that the Bush citadel was assaulted.

Donald Stokes had been dean of the Woodrow Wilson School at Princeton for eighteen years; his 1997 work *Pasteur's Quadrant* fueled the assault.[12] Highly respected at Princeton and as a pioneering political science scholar, he wrote the book while he was dying from leukemia, which gives it a special poignancy. It came out at a moment when the US, despite its amazing leadership in basic research, was too often falling behind its economic competitors in translating its research into technologies.

Stokes explored the causes for this and focused on Bush's design. He understood Japan's contrasting emphasis on applied work to create a strong manufacturing economy, which had enabled the country to seize leadership from the US in the auto sector and much of consumer electronics.

Stokes argued that Bush's basic research canon had two parts: basic research was to be performed without thought to practical ends, and basic research was the pacemaker of technological improvement. On the first point, Bush, in "Science, the Endless Frontier," had sought to persuade policymakers and the nation that attempts to limit the creativity

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of the basic scientist would be self-defeating. On the second, he tried to make the case that investment in basic research would solve the broad spectrum of national needs. As summarized previously, Bush's bargain with the taxpayers was that if government funded basic science, they would see technological advances. The American answer to Sputnik showed how pervasive Bush's ideology spread: it was not simply applied to space research; it also spurred massive increases in basic research, including major funding for the NSF.

Both these premises in Bush's canon came under Stokes's attack. He wrote that Bush's ideal of pure inquiry, of curiosity-driven research, descended from Greek classical science, would not necessarily be the optimal way to pursue advances because it was missing the search for applications. Further, he contended that Bush's link between basic research and technology advance showed what *could* be true—that technological advance could come from basic research—but that it was by no means necessarily or even generally the case. Bush's contention that there was a linear relationship between basic science and technology and that one would yield the other, bore only a limited relationship to their actual connection.

Bush had short-circuited basic research from consideration of use, Stokes argued, and his linear model was one-dimensional. Stokes found that the ties between science and technology aren't linear; they are interactive. Bush's belief was that because understanding and use are conflicting goals, basic and applied research *had to be* separated. Stokes believed this view was misplaced: basic and applied research are in the same system, he argued, and needed *connection* to achieve optimal results in both.

Bush's efforts to protect the autonomy of publicly funded science—which had led him to oppose any efforts to constrain the creativity of basic research—was not the right model; what Stokes called "use-inspired research" was the missing link that would yield both basic and applied results.

Stokes found his test case in the nineteenth-century French chemist Louis Pasteur, who had sought a fundamental understanding of the process of disease through microbiology. He performed this basic research, but with applied research goals such as preventing the spoilage of milk, and then by pursuing vaccines against anthrax in sheep and rabies in animals and humans. As Pasteur's inquiries became more fundamental, they became more applied.

By missing the importance of considering use in research, Stokes contended, Bush had missed a fundamental way that science progressed. From his observations about Pasteur, Stokes advanced his "Pasteur's quadrant" (table 3.1).

Behind the quadrants are two underlying questions about the direction of research: Is there a search for fundamental understanding? Is there consideration of use? Each leads to different types of research.

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Table 3.1
Pasteur's quadrant (by Stokes)

	Is the *use* of the outcomes central to the research? *No*	Is the *use* of the outcomes central to the research? *Yes*
Is the research aimed at ***fundamental understanding***? ***Yes***	Pure basic research—*Example: Nils Bohr*	Use-inspired basic research—*Example: Louis Pasteur*
Is the research aimed at ***fundamental understanding***? ***No***	Reviews of the particulars, not the general—*Example: early Darwin*	Pure applied research—*Example: Thomas Edison*

Source: Stokes (2011, 73).

Stokes placed representative science leaders in the quadrant that they best exemplified. The great nineteenth-century English naturalist Charles Darwin, in his early explorations during his five-year voyage on the *H.M.S. Beagle*, was initially pursuing particulars, not the general, so Stokes placed him in the quadrant where there was no search for fundamental understanding and no consideration of use. Thomas Edison exemplified pure *applied* research in his series of practical inventions, so Stokes assigned him the quadrant where there was clear consideration of use but not a search for fundamental understanding. Niels Bohr, in the days before particle physics led to atomic power, exemplified pure *basic* research, so he went into the quadrant where there was a search for fundamental understanding but no consideration of use. For his part, Pasteur went into the quadrant where there was both clear consideration of use, as well as a search for fundamental understanding. Stokes focused on this "use-inspired" research; this critical quadrant is what he argued was missing from Bush's plans for federal research support.

Of course, we can quibble about whether his examples really fit the quadrants as neatly as Stokes suggests. Edison clearly viewed himself as an inventor, not a scientist; still, his pursuit of practical electric lighting led to underlying ideas about the Edison Effect, an early perspective on electron theory. Darwin's grandfather, Erasmus Darwin, was an early exponent of evolution and the connectedness of life forms, Darwin was fluent with these ideas, and he arrived on the *Beagle* with some definite ideas about why he was on a voyage to the Pacific. And is there really any researcher who pursues neither consideration of use nor a search for fundament understanding? Nevertheless, we see the thrust of Stokes's argument.

This use-inspired research gap, Stokes argued, meant that Bush's linear model flowed in only one direction, from science to technology. It ignores the reverse, where ideas

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from technology development flow back to science. The examples of this are numerous. For example, work at Bell Labs by John Bardeen, Walter Brattain, and William Shockley to develop transistors from semiconducting materials not only led to practical computing but flowed back to spur the entire field of semiconductor science; the three men won the 1956 Nobel Prize in Physics. Edwin Townes developed the maser, a predecessor of the laser, while pursuing microwave research for Bell Labs.

In effect, Stokes argued that technology advances and science require a two-way street, where each can benefit from the other, not Bush's one-way street. In Stokes's design, there would be spaces for basic research as well as applied research, but the largest role would go to use-inspired basic research.

Stokes's closing manifesto was, "A clearer understanding by the scientific and policy communities of the role of use-inspired basic research can help renew the compact that must also provide support for basic research." And he argued that "agendas of use-inspired basic research can be built only by bringing together informed judgements of research promise and societal need."[13]

The linear model missed a major dynamic of science advancement, and Stokes argued that was the deepest flaw in Bush's paradigm. As Deborah Shapley and Rustum Roy put it in their book *Lost at the Frontier*, "What was lost, in a word, was the importance of applied science and engineering."[14] In effect, the US had adopted a flawed model for structuring its organizational design for innovation.

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4 CROSSING THE "VALLEY OF DEATH" BETWEEN RESEARCH AND DEVELOPMENT

American innovation policy has been preoccupied since the late 1990s with the problem of translating its still-strong research into technology development and deployment. Chapter 3 showed how this disconnect was, in effect, engineered into the federal nondefense research and development (R&D) agencies through Vannevar Bush's focus on basic research. By 1998, this disconnect between research and development, basic and applied, became known as the "valley of death."[1] This chapter examines the dimensions of this valley and the bridging mechanisms that have evolved to cross it.

THE VALLEY OF DEATH

Two highly respected science policy researchers, Lewis Branscomb and Philip Auerswald, surveyed the valley in a 2002 paper for the National Institute for Standards and Technology (NIST).[2] They argued that markets for allocating capital to early-stage technology ventures—that is, to cross the valley—were not efficient. Further, they found relatively few mechanisms in place that did cross it.

To portray the valley, they employed a picture, now widely used, from a US House of Representatives Science Committee hearing (figure 4.1).

In response to the market inefficiencies, some institutional arrangements evolved for early-stage funding. But the conditions for success for science-based technology innovation were focused in a few geographic areas characterized by innovator-investor proximity. This was not a space filled by venture capital (VC), so among the gap-fillers, the federal role in early-stage technology transition was by far the most significant. The limited federal funds available for technology development stages, however, were no substitute for private funds; they had to be seen as a complement.

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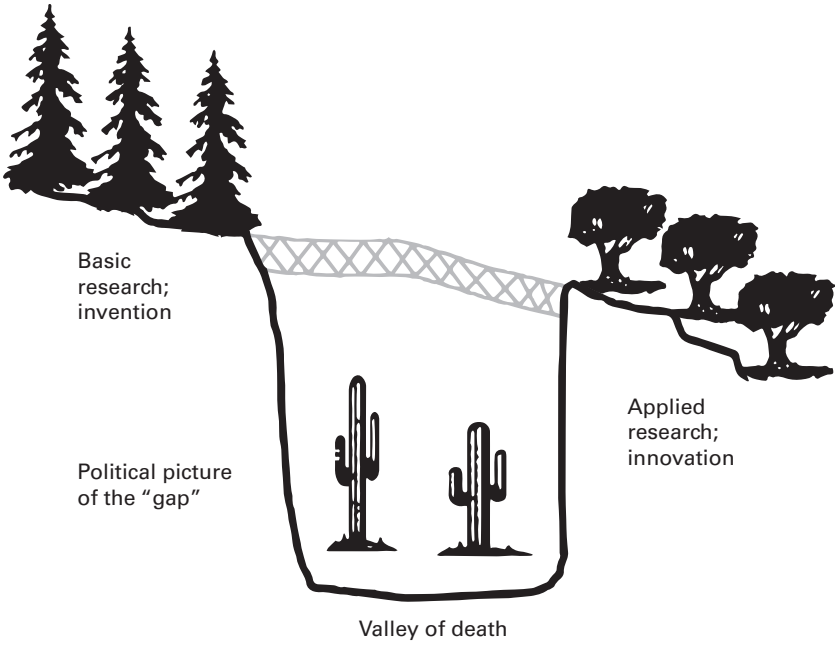

FIGURE 4.1
The valley of death.
Source: Chairman Vernon J. Ehlers, House Science Committee, House of Representatives, Nov. 28, 2000, reproduced in *Source:* Branscomb and Auerswald, "Between Invention and Innovation," 36.

Branscomb and Auerswald developed a depiction of the valley of death (shown in figure 4.2), arranged as a linear model that stretches from basic research through production and marketing and showing the mechanisms for support for each stage. Branscomb and Auerswald found that support varies at each stage, with a major gap at one in particular. Basic research is backed by federal R&D agencies, although not by corporations, while the proof of concept/invention stage has backing from angel investors, companies, some federal technology labs, and the Small Business Innovation Research (SBIR) program. At early-stage technology development (ESTD), however, the gap in bridging mechanisms for the valley of death becomes critical, The actors involved at other stages play only a small role, and VC finds it too high risk. At the next stage, initial product development, VC can step in, and it also can support production and marketing along with other actors, such as some corporate venture funds and equity and debt financing.

ESTD, then, which includes applied research, prototyping, testing and demonstration, and product design, is the area with the weakest support. This is the *deepest* part of the valley of death.

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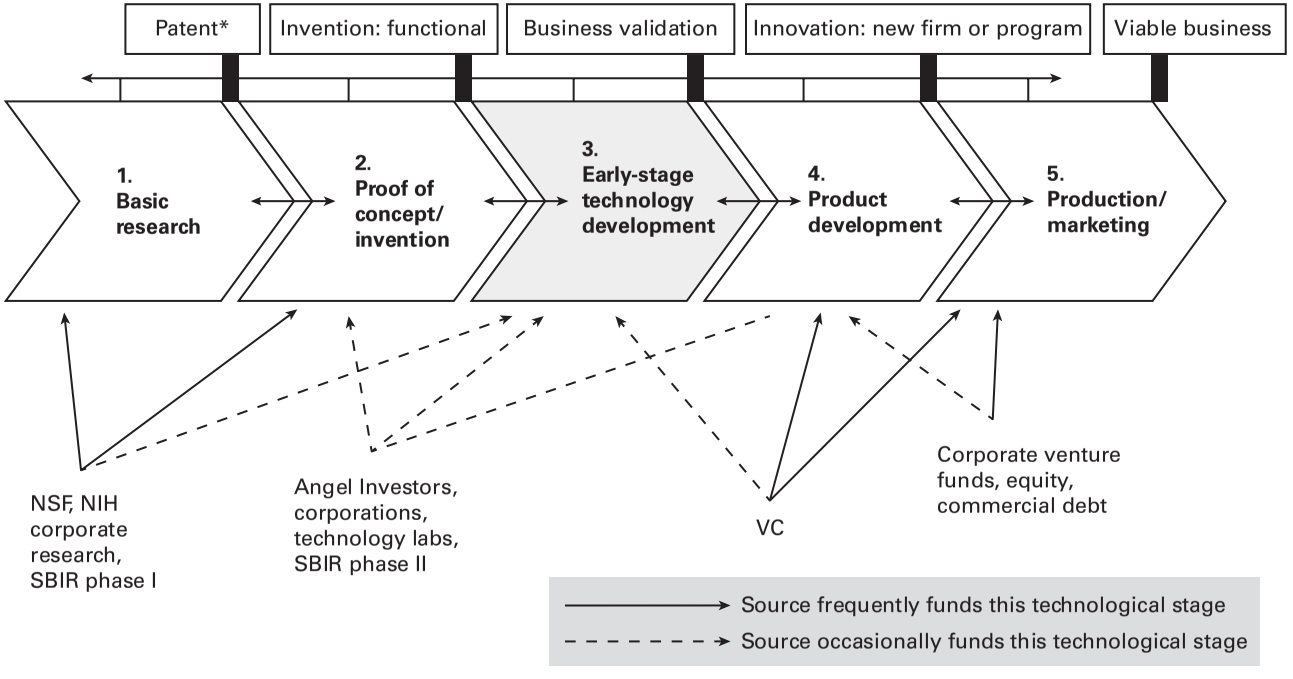
Patent*
Invention: functional
Business validation
Innovation: new firm or program
Viable business
1. Basic research
2. Proof of concept/ invention
3. Early-stage technology development
4. Product development
5. Production/ marketing
NSF, NIH corporate research, SBIR phase I
Angel Investors, corporations, technology labs, SBIR phase II
VC
Corporate venture funds, equity, commercial debt
Source frequently funds this technological stage
Source occasionally funds this technological stage

FIGURE 4.2
Branscomb and Auerwald's linear model.
Source: Branscomb and Auerswald (2002, 33).

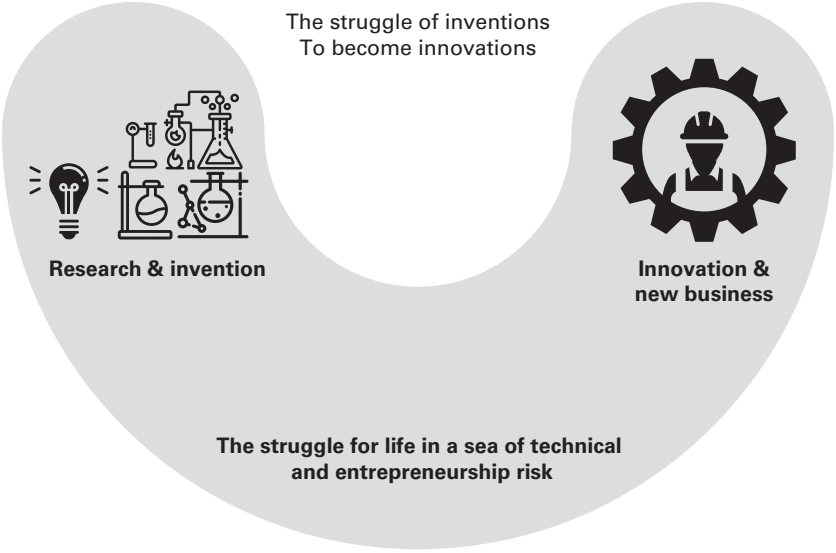

FIGURE 4.3
The Darwinian Sea.
Source: Branscomb and Auerswald (2002, 37).

Reflecting the arguments in *Pasteur's Quadrant* discussed in chapter 3, however, Branscomb and Auerswald note that the linear model is unrealistic. The actual pathway to technology advances, they note, is not linear, but rather full of parallel streams, feedback loops, and linkages that are outside any particular firm or organization. So the one-way direction of their linear chart, they acknowledge, doesn't truly reflect the system's complexity. Instead, between research/invention and innovation/new businesses, there is a proverbial struggle for life that unfolds in a "Darwinian Sea" of technical and entrepreneurial risk, as figure 4.3 illustrates.

In the ESTD stage, as a prototype is developed and moved into product design, product specifications are spelled out, production processes are defined and reduced to practice, and a product cost framework is established. It requires engineering design, design for production, and decisions on product markets. At this stage, VC and corporate support are largely unavailable. VC funding generally goes to product and business development, not to these early efforts.

Corporate innovation support goes only to the firm's core business area, not potential products outside that scope. Corporate management can focus investment on products that complement its own, but only where there is a very strong commercial case. This

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means that corporate support will go overwhelmingly to incremental R&D, not breakthrough new areas. Some firms have their own venture funds, but these tend to follow a VC approach of seeking financial gain.

What about other actors? A few universities have their own venture funds to push university-developed research toward commercialization, often using the Bayh-Dole Act, which gives the university the patent rights to the results that its researchers develop with federal funding. A few states, likewise, have commercialization funds to spur state-based firms.

Angel investors step into ESTD. Family, friends, and now bands of what are referred to as "angels"—small groups of well-to-do, higher-risk investors—make up this group, but it operates at a much smaller scale than VC.

The federal role in this space, while only a fraction of its basic research support, is the most significant; on the nondefense side, this is primarily through its SBIR phase 2 program for scale-up of technology for innovative small firms.

The federal government, then, predominantly supports basic research, while corporations support their own product development. There is a major gap between the two, with relatively few bridges.

A PARALLEL UNIVERSE: THE DEFENSE INNOVATION SYSTEM

The Vannevar Bush universe of basic research is not the only one. The growth economist Vernon Ruttan studied the other. He worked on the economics of agricultural development at the University of Minnesota, studied technical change, became a leading growth economist, and developed theories of "induced innovation," establishing a framework for understanding how firms innovate by spotting a market niche and making largely incremental advances to fill it.[3]

Near the end of his life, Ruttan shifted his focus to how the US defense sector innovates. In *Is War Necessary for Economic Growth?*[4]—an aptly named book—he studied the origins of American production systems for five major technology areas: aviation, space, nuclear power, computing, and the internet, all of which descended from military spending. The book is a classic in the technology development literature.

Ruttan first examined the role of the early federal arsenals. In the late eighteenth century, the fragile new US government faced ongoing threats from European superpowers. President George Washington, a veteran military commander, didn't want to rely solely on private contractors for arms supply. So, in an early exercise of industrial policy, his government established gun-making military arsenals at Harpers Ferry, West Virginia, and Springfield, Massachusetts. Gun-making was a handicraft process, and armies on the

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move required slow-moving logistic tails of blacksmiths and armorers, plus the tools of their trade, to keep their guns in repair. Each handmade musket and rifle was somewhat unique, requiring parts that had to be individually formed, which made the entire enterprise very expensive.

During this same period, Eli Whitney's cotton gin factory in North Haven, Connecticut, failed because his invention could be easily copied—as moderately skilled artisans throughout the South were doing. After failed attempts to enforce his patents, he sought a federal bailout (one of the first in a long history of such business rescues in the US).

Whitney persuaded the War Department to contract with his factory for machine-made muskets with all the parts interchangeable. This would slash musket costs and enable armies to drop their slow-moving armorer wagon trains, instead hauling buckets of identical parts that could be snapped together for rapid repairs. President Thomas Jefferson, an inventor himself, was deeply impressed with the interchangeable parts at a special demonstration that Whitney put on for the government—but despite a decade of trying, he was never quite able to perfect the machine tools to produce the muskets that he promised.

At Harper's Ferry, John Hall of Portland, Maine, who had developed an early breech-loading rifle, became the armorer. He began a long process of creating the machine tools to make interchangeable gun parts. It took six years and $150,000 in War Department funds to meet his 1819 contract to produce 1,000 rifles, but by 1825, Hall and his team had succeeded. Using water power to run machine tools at 3,000 revolutions per minute, he and his group achieved the dimension controls necessary for interchangeable parts—a complete shift from hand-cutting and blacksmithing.

Hall's know-how spread, and the government allowed others to adopt his technologies. In subsequent years, water-powered factories up and down the Connecticut River Valley, and then throughout New England and the Northeast, were making interchangeable parts that enabled the rapid production of low-cost, simple machines ranging from muskets to clocks. British visitors came to these early factories, saw the machine tools and interchangeable parts, and called this the "American System."[5] It was a dramatic innovation.

As all industrial history students know, interchangeable parts were the first critical step on the road to the mass production systems that evolved as the nineteenth century went on. US expertise in interchangeable parts put the country on a path to overtake Britain and dominate world industrial production by the early twentieth century. It was enabled by the US military's willingness to invest long-term, patient capital in pursuit of a high-risk technology advancement that was earnestly desired. The private sector was

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not the innovation driver; rather, it was government industrial policy that spilled over into and transformed the civilian economy.

We will see this pattern again and again in US technology history, from aviation to electronics to space. The role of the US Department of Defense (DOD) in digital computing is particularly significant. During World War II, artillery was a key American military advantage. To get a long-distance artillery shell on target required mastering multiple variables—distance, direction, shell characteristics, elevation, wind, temperature, humidity, and others. Artillery caissons had to carry around a mass of telephone book–size tabular data, and each had to be referenced. It was a perfect task for computing.

When the military added to its arsenal nuclear weapons and the missiles to carry them, the need for computing multiplied. There were other strands in the US military development of computing, including breaking the German military's Enigma codes during the war at Bletchley Park in England, and later at Arlington Hall in Virginia; and as nuclear weapons and missiles became Cold War priorities, computing efforts accelerated.

Early computers began evolving to meet defense needs. An early effort at the University of Pennsylvania, using architecture developed by John von Neumann, led to the creation of the ENIAC computer. Jay Forrester and a team at the Massachusetts Institute of Technology (MIT) worked to develop the Whirlwind, another early computer, for the US navy. Used for flight simulation, it needed to be bigger than room size, and to do its work in real time, it needed to be more than just a calculator, so it required memory storage. Forrester and a graduate student researcher created the magnetic core memory, a crucial advance.

Although the MIT group was making good progress on development, funding problems ultimately forced the Navy to drop the project. Forrester had a computer, but he needed funding and a mission.

One day, Forrester bumped into George Valley in MIT's "Infinite Corridor," which runs through its massive group of main campus buildings. Valley, a veteran of MIT's World War II Rad Lab (described in chapter 3) and its development of radar, had become a science advisor to the US air force after the war. In that role, he had become frantically concerned by a major Cold War problem: Russia had developed both the atomic bomb and a long-range bomber to deliver it. Flying over the Arctic, these aircraft could reach many major cities in the US, which had no warning system or defenses in place. Russia had developed a first-strike capability against an extremely vulnerable US.

Valley persuaded the Air Force that it had to address this problem. He saw that a warning and defense system would require the consideration of countless variables with limited time to respond, and he needed a computer. Forrester had one, and it was being developed to operate in real time—a critical feature.

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Whirlwind, the first real-time computer, had many impressive characteristics. It was arranged on tall racks in a very large room, at the center of which sat an operator with a keyboard in front of a cathode ray screen. Sound familiar? These are elements in the personal computer (PC) and the essence of the laptop. Operators could also point to the screen to access data with a light pen—an early version of mouse functionality.

Valley placed Forrester's Whirlwind computers at the information-receiving points for a new computer-enabled air defense system called the Semi-Automatic Ground Environment (SAGE), which patrolled the Arctic and the North Atlantic by air and sea and was connected to a new network of surface-to-air missiles. Much of the communication was by digital signals transmitted over dedicated telephone lines—an early internet-type system.

MIT didn't want to get into the business of manufacturing computers, so its Whirlwind/SAGE prototype became the basis for the IBM 700 series, which enabled IBM's large-scale entry into early mainframe computing. The computing revolution was underway, with the DOD playing a direct supporting role.

Mainframe and real-time computing was only part of DOD's computing story. In the shift from vacuum tubes to semiconductors, advances in transistors were backed by initial contracts from the department. The next two big steps, the integrated circuit (led by Robert Noyce of Fairchild Semiconductor and Jack Kilby of Texas Instruments) and the microprocessor (led by Fairchild Semiconductor's successor, Intel), were both backed by DOD contracts and purchases for programs such as the Minuteman missile, and by the National Aeronautics and Space Administration (NASA) for the Apollo Project to the Moon. For the first four years, DOD and NASA completely dominated the market for integrated circuits. Later, when the US fell behind Japan's Canon and Nikon in semiconductor chipmaking, Noyce formed the Sematech project as an industry consortium to restore US leadership in semiconductor manufacturing, backed by $500 million over five years from the Defense Advanced Research Projects Agency (DARPA).

Nuclear weapon and missile design required supercomputing. The Cray machines that initially led the field were backed by DOD and US Department of Energy (DOE) labs—and these agencies continue to lead the market for the current generations of these machines. For quite some time, DOD was also the largest supporter of software. The work of Grace Hopper, a legendary computer scientist and US Navy rear admiral, to develop high-level English-language programming was backed by a DOD-supported committee that she led, and the resulting language, COBOL, is still used today. DARPA also funded the early US university computer science departments where software programming was at the heart of the curriculum. (DOD's role via DARPA in personal computing and the internet is the subject of chapter 6.)

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Computing was only one of the innovation waves led by DOD in the twentieth century. Aviation, much of electronics, nuclear power, space, and the internet were others.

ASSESSING THE GOVERNMENT ROLE

The analyst Glenn Fong quotes John Sununu, chief of staff to President George H. W. Bush, as having once flatly stated, "We don't do industrial policy"—and Fong then goes on to estimate that by 2000, the US was spending more than $100 billion a year in tax incentives, subsidies, and credits for industry.[6] His case studies are snapshots of the federal role in fostering computing during the 1980s and 1990s. It is overwhelmingly a DOD story.

Examining DARPA, Fong noted its role in ARPANET (the internet); Sketchpad (for computer graphics); the Strategic Computing program, which led to advances in microelectronics; Very Large Scale Integration (VLSI), integrating millions of transistors on a single chip; parallel processing (breaking tasks up among multiple computer processors); artificial intelligence (AI); Sematech, to restore US leadership in semiconductor manufacturing through improved quality and throughput; and the Advanced Lithography program, to etch chips at ever-smaller scale, enabling a continuation of Moore's Law.

DOD's office responsible for acquisition, technology, and logistics supported the Very High-Speed Integrated Circuit Program (VHSIC), a ten-year project for advanced data signaling that contributed several critical advances in computing, including the Berkeley Software Distribution (BSD) Unix operating system, the reduced instruction set computer (RISC) processor, and the Metal Oxide Semiconductor Research Service (MOSIS) research design, and greatly furthered the Carver Mead and Lynn Conway–led revolution in automating VLSI design. The office also supported the National Flat Panel Display Initiative, to create a new generation of display technologies—although this was ultimately unable to restore US leadership to the sector. Further, a multiagency group that included DARPA created the High-Performance Computing and Communications (HPCC) program, which implemented a wide range of computing advances in high-speed processing and telecommunications, related software and algorithms, a national information infrastructure, and many related applications. These snapshots from Fong illustrated the increasing capability of the federal government to craft major technology advances.

By 2000, according to Fong, the information technology (IT) sector had become the nation's largest in terms of output, accounting for 8 percent of the US total, along with 7.4 million employees earning wages 64 percent higher than average.[7] Some 45 percent of US industrial growth in the 1990s can be traced to IT.

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Mainstream economists had no confidence in the ability of the federal government, particularly through DOD, to foster economic advance. But the stunning collection of IT program snapshots show the opposite. The US was embarking, with spin-offs from DOD military research, on industrial policy at scale (discussed further in chapter 12). Unlike civilian agencies, DOD was erecting major bridges over the valley of death.

Fong found that DOD was employing four underlying models of federal intervention:

- The *by-product model*, in which military R&D led to unintended spillover into the commercial sector through programs such as Sketchpad, for computer graphics, and ARPANET, which created the internet
- The *intentional spin-off model,* in which commercial spin-offs were expressly contemplated during program planning and implementation, realized through programs such as VHSIC and Strategic Computing
- An *explicit dual-use model*, which featured defense technology projects with the explicit goal of meeting commercial and military needs, realized through programs such as HPCC and Advanced Lithography
- The *industrial base model*, which sought to retain an industrial base on the commercial side that would assure military benefits, such as through Sematech and the National Flat Panel Display Initiative

A fifth model, *economic competitiveness*, was applied outside DOD, with support for technology advances at companies. The justification was competitiveness, not national security, and support was solely to obtain commercially relevant technologies. The Advanced Technology Program (ATP), which supported technology advances at companies through NIST, is an example typical of the time. Congress ultimately eliminated ATP, but the national security rationale behind the other four models proved more enduring.

Overall, the snapshots show DOD playing a central role in US leadership of the 1990s IT revolution and the corresponding period of rapid economic growth that characterized that decade. It was systematically getting across the valley of death.

IN-Q-TEL AT THE EDGE OF THE FEDERAL ROLE

In-Q-Tel is an example of just how far down the innovation pipeline the national security rationale could extend.[8] In the 1990s, the Central Intelligence Agency (CIA) saw that it was falling behind, in both its understanding of new IT and its ability to utilize it. The CIA was not new to technology development; in aviation and space, for example, it was behind the remarkable U2 and SR-71 Blackbird reconnaissance aircraft that came out of Lockheed's Skunk Works, as well as spy satellites. But CIA leaders felt that the agency was

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disconnected from the creative forces that were building the digital economy, couldn't compete with the private sector for creative talent, and had little understanding of the evolving internet communications system.

Ruth David, a CIA deputy director for science and technology, designed a unique response to the IT revolution: In-Q-Tel, which is essentially a VC firm owned by the CIA and aimed at ESTD. The "Q" in its name is a nod to the fictional inventor who supplies cutting-edge technologies to Agent 007, James Bond.

In-Q-Tel was founded in 1999 as a private-sector, nonprofit firm to employ technology developed in companies—and it continues to operate today. Its first chief executive officer (CEO) came from a Silicon Valley VC firm, and it formed a talented board of technology and business experts tied to IT innovators, academic researchers, other VC firms, and tech companies, from which it drew its thirty employees.

The company was empowered to create joint ventures and could co-own companies by taking equity positions in firms. It can also fund sole-source development grants and set up open competitions—powers that go well beyond DOD agencies awarding contracts for research.

While the CIA founded I-Q-Tel, it does not review the firm's business deals; the firm collaborates with, but is largely independent of, the agency. From the outset, it aimed to be agile and able to respond quickly to CIA needs and opportunities; to be problem-driven, responding to technology challenges; and to focus on solutions, undertaking applied development for new technologies and products. I-Q-Tel was team-oriented from the beginning and drew technology-fluent talent from diverse sectors to solve problems. Its quantifiable results were innovative and moved beyond the current state of the art.

I-Q-Tel's initial funding from the CIA was $28 million; by 2016, its share of the firm's valuation had grown to $120 million. In-Q-Tel has focused on software, digital infrastructure, and materials sciences.

Federal R&D agencies typically provide awards for R&D efforts, so I-Q-Tel's ability to take ownership positions in firms to influence their product directions, intervening directly in markets and sharing in profits and gains in pursuit of federal aims, made it unique when it began: it was a venture firm. For example, In-Q-Tel backed development work at the firm Keyhole for satellite-mapping software technology; it later sold its interest in Keyhole to Google, where it became Google Earth. Through these kinds of transactions, In-Q-Tel has demonstrated how far a national security rationale could take federal involvement in the innovation system. In-Q-Tel didn't just bridge across the valley of death; it backed companies to fill in the gap.

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FOUR PERIODS OF ATTEMPTS TO CROSS THE VALLEY OF DEATH

So far, we have portrayed the limited mechanisms on the nondefense side of the US innovation economy to bridge the valley of death, along with the many mechanisms that have evolved on the defense side. Let's now take a broader look at this problem and the gradual shifts in US policy toward the valley.

Since the end of World War II, the federal government has moved through four periods of approaches aimed at forming more extensive bridging mechanisms. In each, it has tried to reconnect, even if only partially, the different actors in its innovation system in the development and implementation stages beyond research.[9]

The *first period* was the Cold War, which began in earnest with the Korean War in 1950 and featured the military working to reconnect the key actors. For example, new nuclear weapons labs, including Lawrence Livermore National Laboratory and Sandia National Laboratories, pushed atomic development, and the need for an air defense system accelerated real-time computing through the Whirlwind and SAGE projects noted earlier in this chapter. The 1957 Sputnik crisis led to the creation in 1958 of NASA and DARPA.

The DOD could not work with a disconnected system, so it returned to its World War II–era connected model. As we have seen from examples in computing, it built a system that supported not only research but also development, prototyping, testing, and demonstration, and often created the initial market as well. In contrast, the federal government's civilian R&D agencies supported research only through ESTD. This meant, as previously suggested, that the US had been running two very different innovation systems in parallel—a disconnected civilian system and a connected defense system.

DARPA exemplified this defense connectedness. Its "right-left" approach identified potential breakthrough technologies on the right side of the innovation pipeline, the *output* side, and then went back to the left side of the pipeline, the *input* side, to nurture the science needed to get there. DARPA had no interest in incremental improvements, only revolutionary advances. Its reach across both science and technology was a dramatic contrast to the curiosity-driven basic research supported by Bush's model.[10] It was not just the "use-inspired" research of Donald Stokes.[11] It was use *driven*.

NASA's push for Moon landings through the *Apollo* mission was another effort to cross the valley of death in that era, creating a major space technology and satellite communications sector that in recent years has been commercializing at large scale. Its race to develop the highly reliable first desktop computers, undertaken through the Draper Lab at MIT, was vital to guiding the *Apollo* landers when they were on the far side of the Moon and out of range of NASA's mainframes; this helped accelerate the digital era.[12] This system of defense and national security support for technology development and follow-on product procurement played a central role in most of the major innovation

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waves of the second half of the twentieth century, including aviation, space, nuclear power, electronics, computing, and the internet.[13]

The *second* period was the era of competitiveness with Japan in the 1970s and 1980s. Japan made technology and process advances in production that the US missed, leading to its quality manufacturing system. American policymakers became concerned that although the US was originating the leading innovations, its disconnected innovation pipeline limited the ability to commercialize them.[14] Japan used its quality manufacturing system to capture industrial leadership, previously held by the US, in the automotive and consumer electronics sectors. The result was the "Rust Belt"—declining industrial areas in the Midwest and Northeast. The US is still playing catch-up after taking years to understand Japan's manufacturing quality advances.

During this period, the US also launched some new policies with elements aimed at helping innovators get across the valley of death. The Bayh-Dole Act of 1980 assigned ownership of federally funded research results to the universities where the research was undertaken, giving these institutions a stake in their commercialization.[15] Typically, universities share these rights with the researcher inventors on their faculties and in their labs, incentivizing them to implement their ideas. The new law has proved particularly useful in supporting the biotech sector, in which biotech companies frequently spring out of university research.[16]

Another element, the Manufacturing Extension Partnership (MEP) program, was authorized in 1988 to bring the latest manufacturing technologies and processes to small and medium-sized manufacturers around the nation, as these firms play such an important part in US manufacturing output.[17] It was designed to emulate Japan's quality manufacturing approaches—often called "lean manufacturing." Since then, MEP has worked with thousands of manufacturers, and a thirtieth-anniversary study maintained that MEP centers had already delivered some $18.8 billion in cost savings and $111.3 billion in increased or retained sales per year to participating manufacturers.[18]

The SBIR program began in 1982 and has been another successful valley of death program model.[19] It offers competitive R&D grant funding to small and start-up companies. A related program, the Small Business Technology Transfer (STTR) program, focuses on university-originated start-ups. These two competitive programs attempt to make small, high-tech, innovative businesses a part of the federal government's R&D efforts. Twelve federal departments and agencies participate in the SBIR program through required set-asides from their total R&D funding, and five participate in the STTR program. SBIR and STTR award more than $3 billion to small businesses annually.

An R&D tax credit (officially, the Research and Experimentation Tax Credit) was enacted in 1981 as part of that year's Economic Recovery Tax Act to incentivize innovation by US companies, rewarding them for increasing their investment in R&D in any

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given tax year. Previously subject to renewal, it was made permanent in 2015 and is available to firms for developing new, improved, or technologically advanced products or processes.[20]

Another program, Sematech (as noted previously), was the US response in the 1980s to a massive challenge to the US semiconductor industry from Japanese competitors, who began to dominate market share through lower-cost, higher-quality chip production systems. The program initially focused on semiconductor equipment makers to improve chip-manufacturing processes. DARPA matched Sematech funding from 1991 until 1996. The effort reversed many industry production problems, and the US industry returned to being the world's technology leader, which lasted until around 2018 (as discussed in chapter 12).[21]

Another innovative program of the era, the ATP (also briefly noted earlier in this chapter), was based at the Commerce Department's NIST and funded innovative technology development R&D projects at companies. Congress discontinued the program in 2011; conservatives felt that its aid to companies was too interventionist.[22]

Together, all these elements have been targeted federal economic interventions in the innovation process that have spurred particular sectors or segments, such as innovative smaller firms and small manufacturers, to improve their competitive posture. The general success of these programs has encouraged subsequent efforts.

A *third period* centered around efforts to tackle climate change through energy innovation at the DOE, beginning in the Clinton and particularly during the Obama administrations. DOE shifted from an agency organized around fossil fuels, nuclear power, basic physical science research, nuclear stockpiles, and nuclear cleanup to much more of a new technology innovation organization confronting climate change. The older pieces remained, but DOE added an Advanced Research Projects Agency–Energy (ARPA-E); major renewable energy programs at an expanded Energy Efficiency and Renewable Energy (EERE) Office; an Advanced Manufacturing Office to enable production of the new energy technologies; a Loan Programs Office for scale-up of new energy technology projects; Energy Frontier Research Centers to grow university research in new energy technologies; Energy Innovation Hubs for accelerating development and introduction of core new energy technology; the SunShot Initiative for solar energy advances; and a Technology Transition Office to improve the commercialization of technologies emerging from DOE and its labs.[23] Regulatory programs were also expanded to drive technology shifts and meet climate goals, with energy-efficiency standards reaching new sectors.

ARPA-E was emblematic of the new approaches.[24] It embraced the DARPA "right-left" model of envisioning needed new energy technology advances on the right (output) side of the energy innovation pipeline and then pursuing the needed R&D breakthroughs on

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the left (input) side of the pipeline to get there. But DOE lacked a procurement program like DOD had to drive its technologies into markets, which meant that ARPA-E lacked an implementation partner. Its designers originally planned to use the robust US VC system to get there, but in 2008–2009, VCs backed out of energy technology because they considered it too risky and long term. So ARPA-E had to get creative, funding only those projects with a reasonable road map toward market acceptance, and using DOE-applied programs to help with scale-up after ARPA-E's initial investments.

Critically, ARPA-E established a Tech-to-Market team in the agency, bringing in private-sector expertise to help develop commercialization plans for each project. DARPA later copied this capability—an example of the famous parent learning from the new child.

DOE has applied programs that could fund companies for technology development, and it has a loan program. For example, loans helped scale up numerous renewable energy start-ups and saved Tesla from bankruptcy in the 2008 recession (discussed further in chapter 12), thereby allowing it to become the leading US producer of electric vehicles (EVs).

The loan office did have one notable failure, though, and that led to a highly political outcry against federal intervention. Solyndra had an advanced thin-film solar technology, backed by a DOE loan, that couldn't compete with low-cost but less efficient solar photovoltaics dumped into US markets by Chinese manufacturers.[25] But this political firefight did not affect the many more-successful DOE efforts to bridge the valley of death in what remains an ongoing effort.

The *fourth period* involves advanced manufacturing. As reviewed in chapter 9, US manufacturing never fully recovered from its problems competing with Japan's quality model in the 1970s and 1980s. And when China rose in a remarkably short period to displace the US as the world's largest manufacturer, US manufacturing experienced a disastrous decade from 2000 to 2010.[26] Manufacturing employment declined by one-third in that period, mostly due to global competition from China, not higher productivity; by 2019, the US had recovered only one-fifth of the nearly 6 million jobs that it lost.[27] Manufacturing fixed-plant investment declined as well during that period, and US manufacturing output returned to its 2000 level only in 2018.

Currently, US manufacturing productivity growth has fallen to historically low levels, lagging its major competitors.[28] It runs an enormous trade deficit in goods, reaching $913 billion in 2020,[29] including a $244 billion deficit in advanced technology goods in 2021.[30] The result, beginning around 2000, has been extensive social disruption, with an increasing portion of the American working class losing middle-skilled jobs in favor of lower-end service-sector jobs, thus creating rising income inequality (until the post-COVID tight labor markets).[31]

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US policymakers were very slow to see the implications of the nation's production decline. But by 2012, they began to pay attention to the innovation side of manufacturing. Taking a page from both Sematech and Germany's Fraunhofer Institutes, the US created sixteen manufacturing innovation institutes.[32] Each is organized around a particular strand of advanced manufacturing technology, including additive manufacturing, digital production, robotics, power electronics, biofabrication, flexible electronics, and photonics. Each institute is a consortium of large and small producers, area universities and community colleges, and government, with industry, state, and regional support matched by federal government funding. They undertake collaborative applied research around their advanced manufacturing technologies with universities and industry, engage with regional manufacturing ecosystems, and provide workforce education. In short, they return to a more connected model of innovation, incorporating postresearch innovation stages previously outside the federal purview and tying the innovation actors together in a way not previously undertaken in the federal government outside the defense sector.

It is a complex model requiring diverse interests to partner and collaborate, but the institutes have made significant progress. Of the 1,900 member-organizations in the institutes as of 2020, 61 percent are manufacturing firms, and 70 percent of those are small and medium-sized manufacturers with 500 or fewer employees.[33] Total institute expenditures in FY2019 were $488 million, including $133 million in base federal program funds and $355 million in institute-generated funds from industry, academia, economic development, state government, and competitive federal funding.[34] This represents a 2.7-to-1 investment ratio in matching funding to base federal funding. These funds are invested in technology R&D, capital investments such as facility and manufacturing equipment purchases, institute operations, and education and workforce development programs.

Still, total federal funding to the institutes represents an underinvestment in what is required to achieve a manufacturing transformation—it's difficult to implement major change in a $2 trillion manufacturing sector with only $133 million in annual federal funding. There are other programmatic gaps as well, including the inability to help test and finance the new production technologies in companies that are ready to take the risk of experimenting with and adopting them.[35] These issues are explored further in chapter 9.

In summary, the US has engaged in a series of attempts to bridge the valley of death since Vannevar Bush's basic research model built this valley into the US system in the years after World War II. By far, the most significant effort has been exerted by the US defense system, with innovation agencies built and linked to follow-up defense procurement investments. While the investments were made for defense reasons, many of the technologies were dual use, expanding new sectors in the overall economy, including

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space, nuclear power, computing, and the internet. Most of the waves of postwar innovation have come out of this connected system.

Other efforts outside defense were smaller in scope and scale, but they have still been noteworthy and often successful. These include various programs created in response to competitiveness pressures from Japan, new energy technology efforts to address climate change, and, beginning in 2012, an effort to create public-private consortia to develop advanced manufacturing technologies. These defense and nondefense programs have generally fit within the industrial policy definition of governmental policy interventions that alter economic activity in sectors, technologies, or tasks to improve economic prospects in ways that noninterventionist market forces cannot. All of them have tended to share three general approaches: to build on strong US R&D capacity, to intervene to support particular technology sectors, and to take advantage of federal follow-on procurement funding or financing (when it is available).

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5 INNOVATION BY GREAT GROUPS

We have discussed innovation at the institutional level, but *people* are the ones who do the actual innovating. What does innovation look like at the personal, face-to-face level? The short answer is that it occurs through great *groups*.

THE PROCESS OF INVENTION

Innovations are built from inventions, so first let's look at the process of invention. William Rosen, who has written on invention,[1] begins with this observation from the German philosopher Immanuel Kant: "The hand is the window on to the mind."[2] Charles Bell, the Scottish anatomist, neurologist, and theologian, had a concept of the "intelligent hand."[3] The concept speaks to hands-on learning, to mental gymnastics reinforced by physical actions and applications. It calls out the connection between learning and making, the link between thought and practical action that is the heart of invention. The motto of the Massachusetts Institute of Technology (MIT)—*mens et manus*, meaning "mind and hand"—conveys the same idea: that only through application (hand) of theory (mind) can we drive changes and advances.

The concept of learning by doing is a complementary notion. From the pragmatic philosopher and education theorist John Dewey, it held that students must interact with their environment to learn.[4]

There is a visual element, too. Rosen argues that the act of invention relies on the visual and tactile—the mind, eye, and hand together weaving a new pattern.[5] Leonardo da Vinci famously combined drawing and invention—visualizing the invention was central to the advance

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When the Scottish inventor James Watt walked through Glasgow Green that Sabbath spring day in 1765, he enjoyed a famous "flash of insight" into how he could make a steam engine work. He had the idea of a separate condenser that would enable a vacuum to suck in the piston while also allowing the cylinder to maintain its constant temperature, creating a practical steam engine.[6] Toward the end of his life, he wrote of that moment, "I had not walked further than the Golf-house"—this was Scotland, after all—"when the whole thing was arranged in my mind."[7]

Such insights appear effortless, but they are built on the hard work of creating prior knowledge. Six years earlier, Watt had begun studying the Newcomen engine, a steam-driven pump for coal mines, and understanding issues such as latent heat and thermal energy, even though the laws of thermodynamics were still a century away. In 1763, he repaired a Newcomen engine and, finding that most of the thermal energy was wasted in each piston cycle, worked out its fundamental inefficiency. These years of careful study paved the way for his later insight. Then he took another four years to file a patent on his findings, followed by years of incremental improvements before Watt's steam engines were operating in commercial settings.

Watt's extended efforts fit with Anders Ericsson's findings on "expert performance." It was time on the task, not simply talent, that made the difference in being truly outstanding in music, medicine, and chess.[8] Expert performance means hard work and requires repeated action.

Rosen also notes the contributions of the Hungarian-British polymath Michael Polanyi's contributions on the concept of tacit knowledge. Polanyi believed that science and scientific discovery are not value-free; rather, they are driven by strong passions and commitments, with the passions motivating exploratory guesses and hunches. As he famously wrote in 1967, "We can know more than we can tell."

Polanyi was positing a prelogical kind of knowledge that he called "tacit knowledge." It was a collection of conceptual and sensory information and images that could be brought together to understand something (a kind of tactile knowledge) and was the basis for much of discovery. It is knowledge plus skills.[9]

Eric Kandel, the Nobel-winning neuroscientist, contributed an underlying concept that our experiences change our brain chemistry. It suggests that our mix of tactile experiences affect our brain, creating a pathway that helps lead to discovery.

Rosen, in pulling these inventive strands together, saw a pattern in the way the Industrial Revolution in Britain evolved. First, there were craftsmen, who were practically oriented and had limited training. They were followed by instrument makers, who created tools and formed potential inventions. Finally, there was a stage of technical learning during which mathematics joined with the practical learning from these craftsmen and

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instrument makers. Craftmanship, instrumentation, and technical learning must all be integrated into the invention process.

Watt building on the Newcomen engine is an example of this technical learning stage. So, too, is the work of John Smeaton, an eighteenth-century British civil engineer and inventor with math training. He examined the metrics of water flow under, over, and past a waterwheel in a period when streams and rivers provided the essential power for mills and early factories. He systematically varied the flow parameters, carefully recording the results for each, and found that the overshot waterwheel was much more efficient than the undershot waterwheel. He stands for the systematic processes by which inventions can be tested. Systematic evaluation is another strand of the invention process.

The final stage requires scale-up. An invention does not enter the economy on autopilot. It takes relentless effort to improve and perfect an invention through processes of advanced prototyping, demonstration, testing, feedback from testing, and finally design for production and pilot production. Watt's insight on the Glasgow Green came in 1765; it took him more than a decade later for his preproduction processes to play out to enable the technology to start to scale. Very complex and sophisticated efforts are involved; the engineering, reengineering, and application of new science required Watt's full efforts. What we now call research and development (R&D) is not enough.[10]

Rosen's thoughts about the invention process leave us with some core points. Inventors use a mix of mind, eye, and hand to develop a tactile sort of learning that can lead to insights for discovery. The discovery process itself builds on expert practice—as Watt's experience showed, it drew on years of study and practical application. Polanyi suggests that discovery is not simply the result of explicit knowledge acquired through study; it also comes from tacit knowledge built upon tactile learning. Next, there is a process of technical learning applying math and science that refines and improves the process of developing insights. Finally comes the major engineering effort that goes into actual implementation.

Rosen and the other analysts are examining invention, which is typically achieved by individuals. Innovation is a much more complex process. Abbott Payson Usher, a historian of invention, found technological innovation to be a slow, collective process with many contributors. It cannot simply rely on the genius of a particular inventor.[11]

As noted in chapter 1, innovation is built on scientific discovery and breakthrough inventions and is the system for research, development, and invention, applying science and technology to spread advances to commercial or societal use. A simpler, alternative definition is that innovation is the system that operates at the intersection of science and invention to create social and economic value. It requires a much larger effort than "solo" invention; it requires a mix of skills and capabilities from multiple people to

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advance from invention—with all its relevant elements—to innovation. No single person has the full skill set to do it alone.

"GREAT GROUP" THEORY

In a 1997 book, *Organizing Genius*, Warren Bennis and Patricia Ward Biederman argued that innovation stems from groups that tend to share a host of characteristics. The book was written for business school students, so it consists of lessons drawn from case studies; it is not an exercise in social science metrics. But the characteristics that the authors articulate seem to ring true.

Bennis recounts that he got the idea from a discussion with Margaret Mead, the great cultural anthropologist, after a lecture that she gave one snowy night in the late 1950s in Cambridge, Massachusetts. He had been wondering why talented groups were able to accomplish so much more than talented individuals acting alone. He asked Mead what she thought of a book on how networks of gifted people had changed the world. "That's a wonderful idea," she replied, "especially since it's never been done before. You should call it 'Sapiential Circles.'"[12]

With Mead's blessing, Bennis kept considering writing the book, and he and Biederman published it four decades later—with a snappier, less anthropologic title. In their mix of case studies, the authors found characteristics—each described briefly next—that seemed to apply to many of the great groups they studied:[13]

• *Greatness starts with superb people.* In the words of the Advanced Research Projects Agency (ARPA—later known as DARPA, with the "D" added for "Defense" in 1972) and the Xerox Palo Alto Research Center (PARC) leader Bob Taylor, "You can't pile together enough good people to make a great one."[14] The participants in a great group not only have original minds and strong intelligence, but can see across fields and make connections.

• *Great groups and great leaders create each other.* Nontrivial problems require collective solutions. While the public tends to see only the leader, the group is paramount and vital for innovation.

• *Every great group requires a strong leader.* It seems to be a paradox of creative collaboration, but the visionary's dream occurs only if others are free to do great work. The leader needs to be a maestro, leading a talented orchestra as a dreamer who can both see and realize new paradigms. The leader also needs to be worthy of the group. Although there can be numerous leadership styles, tyranny will end a group that needs to collaborate.

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• *Leaders of great groups love talent and find it.* Leaders have to be confident enough to recruit people better than themselves. The broader and more diverse the network, the more effective the group.

• *The talent in great groups can work together.* Innovation requires collaboration, so there must be talent that fosters collaboration. Many innovation-related tasks require individuals working together; those who can't, however bright they may be, jeopardize the joint effort. But this doesn't mean there isn't room for individualism, which also must be respected.

• *Great groups think they are on a mission from "God."* These groups have the zeal of believers. They are not doubters. They see themselves as followers of new truths. They must buy into a common vision of transformation and be prepared to make personal sacrifices for the sake of the group effort.

• *Great groups are islands, but they have a bridge to the mainland.* To change the world, you have to be isolated from it to some degree. These groups build their own culture and language, and even their own jokes. They have to have fun. They need to be protected from interference from bureaucracies, but they also have to have a way to access resources and support that will enable them to follow through.

• *Great groups see themselves as winning underdogs.* They often need to see themselves as feisty Davids going up against Goliaths. For Apple, it was about beating "Big Blue" (i.e., IBM) in personal computing.

• *Great groups have an enemy.* Great groups require an intensity that resembles warfare, and an enemy can spur such intensity. For example, the Manhattan Project faced the threat that the Nazis would be first to develop atomic weapons and win the war overnight. Steve Jobs and the Apple team faced down all the might and resources of the giant IBM.

• *People in great groups "wear blinders"—they only see their project.* They can't be distracted by peripheral concerns. They must focus entirely on achieving their vision.

• *Great groups are optimistic, not realistic.* They need to believe that they can achieve things never before accomplished. Often, because they are young, they don't know their limits.

• *In great groups, the right person is in the right job.* People are not interchangeable; the person and the task need to match

• *Great groups give their talent what they need and free them from everything else.* Great groups must feed the mission, not a bureaucracy. Information has to flow freely among the group. The group needs protection from outside forces, especially the "suits"

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(executives), who don't recognize their need for creativity. The group needs to build morale and keep out stress. The team needs freedom to follow through on its ideas. For all its members to contribute, the group needs to promote democracy, participation, and mutual respect.

- *Great groups have to ship.* Innovation cannot occur if it is an endless dream. It needs to become concrete. A group has to stay grounded and focused and bring its visions to a conclusion by, proverbially, "shipping out" its results.
- *Great work is its own reward.* The payoff is not a monetary reward, but rather the creativity that the task pulls out of team members, as well as the success of the endeavor itself.

The great groups described in the pages that follow have most, if not all, of these characteristics. The examples drawn from the history of innovation in the US not only reinforce the importance of what Bennis and Biederman describe, but enable us to derive some rules for building outstanding teams, which are presented at the end of the chapter. Because great groups require great leaders to build them, each of the case studies here begins with the leaders and then moves to the critical group characteristics. In the end, the cases show that the team is vital, but also that there is no substitute for leadership—so both are emphasized.

EDISON AND THE INVENTION FACTORY AT MENLO PARK (1878–1879)

Thomas Edison formed the archetype for great innovator groups.[15] Home-schooled by his mother, and with only a few months of formal education, he fell in love early on with experiments and technology, became an ace telegraph operator, and then began working on improvements to the telegraph. He developed the multiplex telegraph, which could send multiple messages on the same line—and that caught the eye of Wall Street financiers.

Edison took his profits from these telegraph advances, acquired a farm in Menlo Park, New Jersey, and there established his famous laboratory in a simple 100-foot long wood-frame building. He called it his "invention factory." He hired a team of a dozen or so skilled artisans with a few trained scientists mixed in. Their project, with a limited budget and limited time (until Edison's money ran out), was to develop electric light. They worked intensely, sometimes around the clock, taking midnight breaks together, eating pies, reciting doggerel poems to each other, and singing songs.

One time, Edison—who was often in the lab at night—arrived unexpectedly in the next-door farmhouse. His wife, thinking that he was an intruder, almost shot him. But this anecdote illustrates how hard he and his team were working.

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The Menlo Park team, highly collaborative, mixed a range of disciplines, as briefly summarized in chapter 2. Great groups also require collaborative leaders, and Edison was a remarkable one—disciplined, respected, and intuitively brilliant. He drove the team hard, and they followed his experiment objectives. His team treated him with deference, but he was open to ideas and contributions from all.

While there were various other attempts to develop electric light underway at the time, none had the intensity of Edison's group. The Menlo Park team worked on the idea of filling the gap between electric poles with a filament placed in a vacuum tube, making major progress by November 1879, and finally found a carbonized bamboo filament that could last 1,200 hours. But that was only the breakthrough invention, not the full innovation. To make their light usable, Edison and his team then had to invent much of the infrastructure for electricity—from generators to wiring to fire safety to the structure of a supporting electric utility industry. By 1882, Edison had demonstrated the new system, illuminating a block of Pearl Street in Manhattan. [16]

Edison and his team became inventors and innovators, visionaries and (as initiators of a network of companies with Wall Street backing) vision enablers. Edison gets credit for working out a process of invention with systematically organized scientific experimentation and the diverse team needed for it. He had created the first industrial research lab.

Notably, as part of this process, Edison had to derive elements of electron theory to explain his results, and his "Edison Effect" helped lead to advances in that theory. There is a major lesson in this, noted in chapter 4: science is not simply a linear pipeline going from basic to applied; it goes both ways, from basic to applied and from applied to basic.

Menlo Park was characterized by much of what Bennis and Biederman identified as characteristics of great groups. There was great talent, including in a range of needed fields; the group had the skills, from glassblowers to engineers, that it needed, along with the lab equipment. The group worked well together. It had a strong and effective leader. Team members were focused on their project and wore the proverbial blinders with respect to anything outside the project. They were optimistic, but also understood that the project had to have results before the funding ran out. The group operated as an island on Edison's Menlo Park farm, but they had ties to Wall Street for help in implementing their ideas. And finally, they were well aware of the competition over producing electric light from other groups.

There are some other features particularly worth noting: the team was organized around a technology challenge, with the group trying to achieve a specific goal; it applied an interdisciplinary mix of practical and basic science to get there; and it used a connected science model, tying invention to innovation and incorporating all stages of innovation advance. The group was under Edison's determined leadership, which was

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vital, but at the same time, it was a nonhierarchical, relatively flat, two-level, highly collaborative effort. The team mixed experimentalists and theorists, artisans, and trained scientists and engineers to create a blend of experimental and theoretical capabilities and disciplines.

J. ROBERT OPPENHEIMER AND THE LOS ALAMOS PROJECT (1943–1945)

In 1943, the physicist J. Robert Oppenheimer was named by General Leslie Groves, director of the Manhattan Project to develop the atomic bomb, to lead the project's design branch.[17] Oppenheimer himself selected Los Alamos, in the New Mexico desert, as the site for the bomb design effort; there was a former boys' school campus there that Oppenheimer knew from his own riding and camping experiences, a secure location situated on a high, isolated mesa where the researchers could work undisturbed. The Los Alamos design site was not far from the initial bomb testing site in the New Mexico desert. Many of his fellow physicists recognized Oppenheimer's remarkable brilliance, but they worried about his lack of management experience. But he gained Groves's confidence at the outset, and soon that of the other participating scientists as well.

The physicist (and later Nobel Prize winner) I. I. Rabi and others convinced Oppenheimer to follow the successful Rad Lab model and its great group approach (discussed in chapter 3) in organizing the project, and ten leading Rad Lab scientists, including Rabi and Luis Alverez, brought the Rad Lab culture with them when they left to join the Los Alamos project. Los Alamos had a large number of scientists who were broken into teams organized around key development tasks, just as at the Rad Lab. These teams were flat and nonhierarchical, set up to be collaborative. To ensure collaboration and idea sharing between teams, Oppenheimer held weekly colloquia for all the scientists to update them all on advances and challenges. And, as in the Rad Lab, Oppenheimer kept the military away from the scientists to help prevent the military bureaucracy from limiting the scientific collaboration.

Oppenheimer himself functioned as a catalyst, circulating between teams. One scientist described his leadership style as being like a bee spreading pollen.

The work of the Los Alamos group exemplifies what I call the "technology challenge model." The scientists were desperate to beat the Germans to atomic weapons, which everyone understood would win the war as soon as they could be deployed. Many of them knew Werner Heisenberg, the brilliant physicist who was leading the German effort, and most thought that he was well ahead in the race and that they were playing catch-up. Jenet Conant's book on the project, *109 East Palace,* quotes Stanislaw Ulam, a leading physicist there, who characterizes the atmosphere:

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> Equally striking to Ulam as the cooperation was the conviviality, not only among the physicists, both theoretical and experimental, who differed greatly in temperament, but also among the mathematicians, chemists, and engineers. "People visited each other constantly at all hours after work," he wrote. "They considered not only the main problem—the construction off the atomic bomb and related physical questions about phenomena that would attend the explosion—the strictly project work—but also general questions about the nature of physics, the future of physics, the impact of nuclear experiments on technology of the future, and contrastingly its influence on the future development of theory." Beyond this there were wide-ranging discussions of the philosophy of science, and of course the world situation, from daily progress on the war fronts to the prospects of victory in the months to come. "The intellectual quality of so many interesting persons and their being constantly together was unique. In the entire history of science there had never been anything even remotely approaching such a concentration."[18]

The group certainly exemplifies a number of the great group characteristics spelled out here. It was full of superb scientists. Oppenheimer was a remarkable leader, brilliant enough to keep up with each of his teams and contribute to them, but also to get them to contribute to each other. The group could work together, with the right person in the right job. Team members were zealous in their work and wore blinders, focusing solely on their own part of the project. They faced a dangerous enemy, Nazi Germany, which they had to beat to win the war. They had immense resources from the government and whatever equipment they required. And they were an island on their isolated mesa top, but with a bridge to the nation's top political and military leaders. They also exemplified some of the other features discussed here: they pursued an intense technology challenge; their team was structured as flat and nonhierarchical; and they pursued a connected science model that brought together basic and applied research from a series of relevant fields, all the way through the engineering and production stages.

BELL LABS TRANSISTOR TEAM (1947)

Like Edison's Menlo Park lab, the Murray Hill facility of Bell Labs was set in the New Jersey countryside. It drew scientists from the two great World War II–era labs, the Rad Lab and Los Alamos.

Mervin Kelly, AT&T's vice president for R&D, and William Shockley, his lead researcher, wanted to put together a team of fifty scientists and technicians from various fields who could do fundamental research leading to practical applications. Their task was to develop a replacement for vacuum tubes, based on solid-state physics, so AT&T's switching capability could continue to advance telephone speed and capacity.

John Bardeen and Walter Brattain, two of the leading solid-state physics researchers who joined the team, developed a profoundly close collaboration. One was a theorist

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and the other an experimentalist. One was outgoing, and the other was reflective. Their scientific and personal skills were a match. They were friends outside of work and held a strong mutual respect. Backed up by the deep industrial technical support system at Bell Labs, with the latest equipment and very strong technical staff, the two entered a "magic month" in mid-November 1947, and by December 16, they had developed the first transistor.

As Bardeen's biographers put it, "The solid-state group divided up the tasks: Brattain studied surface properties such as contact potential; Pearson looked at bulk properties such as the mobility of holes and electrons; and Gibney contributed his knowledge of the physical chemistry of surfaces. Bardeen and Shockley followed the work of all members, offering suggestions and conceptualizing the work."[19]

Brattain later commented:

> It was probably one of the greatest research teams ever pulled together on a problem . . . I cannot overemphasize the rapport of this group. We would meet together to discuss important steps almost on the spur of the moment of an afternoon. We would discuss things freely. I think many of us had ideas in these discussion groups, one person's remarks suggesting an idea to another. We went to the heart of many things during the existence of this group, and always when we got to the place where something needed to be done, experimental or theoretical, there was never any question as to who was the appropriate man in the group to do it.[20]

Unfortunately, Shockley wrecked further working collaboration in the group when he attempted to garner credit for himself for Bardeen's and Brattain's work, and then worked alone at his home designing a further breakthrough improvement—a semiconductor "sandwich" to replace the transistor's electrical contact point—without telling the rest of the group.

Before its trust declined, however, the team exhibited many of the Bennis and Biederman characteristics of great groups. It was superbly talented, relatively nonhierarchical, and relatively flat organizationally, with essentially two levels. The team was highly collaborative, bringing to bear a range of expertise and disciplines, including theorists and experimentalists—with each participant working in his strongest skill area. The group wore blinders to focus on the project, especially in the "magic month"; enjoyed high morale; and had the latest equipment. The group traded ideas on a continual basis, meeting frequently, with each providing thoughts to assist the progress of others. It was organized on a technology challenge model, and while it worked on a Bell Labs island, it still had ties to decision-makers. The connection to Mervin Kelly ensured that they had a link to a decision-maker among AT&T executives who could facilitate development of the group's breakthroughs.

Bardeen and Shockley played leadership roles, moving conceptual ideas among the group. Shockley, though, also exemplified the tyranny problem: namely, that an

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egocentric leader can disrupt the collaborative foundations of a group. This was a characteristic of Shockley even outside of Bell Labs. After he drove Bardeen and Brattain away from follow-on transistor efforts, he left Bell Labs to found his own company, Shockley Semiconductor, only to drive away his talented team there—which included Robert Noyce, who developed integrated circuits, and Gordon Moore, of Moore's Law fame, who went on to become cofounders of Intel.[21]

GRACE HOPPER AND THE LANGUAGE OF SOFTWARE

Grace Hopper (introduced in chapter 4) studied mathematics at Vassar College, earned a PhD in math at Yale University, and then returned to Vassar to teach.[22] When World War II broke out, she joined the Naval Reserve, and, in 1944, she worked with Howard Aiken and a Navy-supported team at Harvard University that was building an early mainframe computer, the Mark I. She was one of the first computer programmers.

After the war, and still in the Naval Reserve, Hopper joined the start-up Eckert-Mauchly Computer Corporation as senior mathematician. She was part of the team, initially formed at the University of Pennsylvania, that built another early mainframe, the UNIVAC I.

Hopper, though, was not interested in hardware ("the part of the computer you can kick," she said).[23] She focused on the speed of writing instructions for mainframes. At the start-up, Eckert did the hardware, and Mauchly and Hopper did the logic—the information flow, the instructions. Initially, there were no computer languages, only "assembly codes," and each was different for each machine. Hopper commented, "Some mathematicians look down on computers because they are applications. They get very snooty. But I have my PhD in math so I turn my back on them."[24]

At Eckert–Mauchly, Hopper worked on the software and, over time, built her team. She led the development of one of the first compilers, a program that can translate source code from an abstract, high-level programming language to a less-abstract, lower-level language (i.e., an assembly language or machine code to form an executable program). She had been told that machines would never understand a programming language based on English, but she persisted in developing less mathematical, more straightforward, and intuitive programming. Her compiler, which she completed in 1952, converted English terms to the machine code understood by computers.

She said of her compiler:

> [It] translated mathematical notation into machine code. Manipulating symbols was fine for mathematicians but it was no good for data processors who were not symbol manipulators. Very few people are really symbol manipulators. If they are they become professional mathematicians, not data processors. It's much easier for most people to write an English statement than it is to use symbols. So I decided data processors ought to be able to write their programs

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> in English, and the computers would translate them into machine code. That was the beginning of COBOL, a computer language for data processors.[25]

In 1954, Eckert–Mauchly chose Hopper to head up a department for automatic programming that released some of the first compiled languages, including FLOW-MATIC. She led a close-knit group that was known in the company as "the little UN" because of the diversity of nations and races represented on her programming team. Control of the company shifted in the 1950s to Remington Rand, and later to Unisys, but she kept building strong programming teams. Meanwhile, she was elevated in 1957 to a commander in the Naval Reserve.

In 1959, the US Department of Defense (DOD) formed a consortium of computer experts from industry and government—including Hopper and some of her former team members—as the Conference/Committee on Data Systems Languages (CODASYL). Hopper, there to guide the creation of a machine-independent programming language, became the de facto leader. Her cause, and that of her team, was a standard, simpler software language. The DOD supported her aims because it also wanted programming compatibility across the many computer vendors that it was using. CODASYL defined the new language, which extended Hopper's FLOW-MATIC language with some ideas from the IBM equivalent, COMTRAN. It was a critical moment in the history of software. Ultimately, in 1959, CODASYL created a new business language, COBOL (for common business-oriented language), which allowed writing in a language close to English and went on to be the most ubiquitous business language to date.

Hopper herself eventually went on to active duty in the Navy advising on computing, retiring as a rear admiral. A US Navy destroyer, a supercomputer, and a college at Yale were later named for her.

A number of the Bennis and Biederman characteristics match her group at Eckert-Mauchly and later at CODASYL, including assembling great talent; the combination of a strong and determined leader with collaboration across the group; the focus on their complex software task (wearing "blinders"); optimism, not realism, in pursing their task amid concerns that it was impossible; and the needed resources and equipment. Hopper's teams also pursued a technology challenge; the organization was relatively flat, with only two levels; and the effort exemplifies connected science, moving from math to software applications.

THE WOMEN OF *HIDDEN FIGURES* AT NACA/NASA

A 2016 film titled *Hidden Figures*[26] tells the story (adapted by Hollywood, of course) of a group of African American women who worked for the National Aeronautics and Space

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Administration (NASA) at its Langley Research Center in Hampton, Virginia, in 1961. It's how most Americans know anything about this group. The actual story begins well before the film's time frame and is far richer than the Hollywood version.[27]

The women had been math teachers in the South's segregated public schools, but new opportunities opened during the World War II labor shortage, when men were overseas. As the aviation industry continued to expand in the US after the war, people with math skills were needed. This offered these women chances for jobs that met their skills. They were hired by the National Advisory Council for Aeronautics (NACA), NASA's predecessor, to work at the Langley facility. Prior to electronic computing, women with prodigious calculating skills often served as "human computers," and these were the positions they filled.

The US armed services themselves had been officially integrated in 1948, but Langley observed Virginia's Jim Crow laws, which required that Black workers be segregated from their white counterparts. Eventually, though, these women—who constituted Langley's all-Black West Area Computing group—moved into a series of roles as the space race became a national focus, playing a critical role in the effort to get astronauts into space. (As NACA was turned into NASA, the segregated group was disbanded in 1958.)

Among the group, Mary Jackson was assigned to the space capsule heat shield team and promptly identified and helped solve a key design problem; despite segregation, she obtained additional education and became NASA's first Black engineer. When an IBM 7090 computer arrived and threatened to replace human computers, Dorothy Vaughn taught herself and her West Area Computing group IBM's Fortran programming language, enabling them to play an enlarged role; she was the first African American appointed as a supervisor, heading the West Area Computing group.

Among the group, Katherine Johnson had a particularly emblematic career at NASA. From 1952 to 1958, she worked as a "human computer," performing calculation and projections on topics such as gust alleviation for aircraft. Then, because of her graduate work and skills in analytic geometry, she became the first Black woman to be an aerospace technologist in the space task group and calculated rocket trajectories for both the *Mercury* and *Apollo* missions. She plotted the trajectory of Alan Shepard, the first American in space, and used electronic calculators for the first time to plot John Glenn's earth orbit. Any error would have led to disaster, and Glenn had asked for her specifically to review his trajectories. Her work helped ensure that the astronauts could be picked up quickly after landing at sea.

Later, Johnson worked directly with digital computers and on the *Apollo* flights to the Moon. When the *Apollo* 13 mission aborted, she helped set the path for its safe return,

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creating a one-star observation system that allowed accurate location setting for the astronauts.

Johnson, brought over to support the space task group in NASA's early days, once spotted an error in a white male engineer's calculation she was checking and told him of the mistake. "I'd crossed a social line, and everyone froze. I could almost hear some of the engineers thinking, who is she a Colored woman to question a White male engineer." [But] I was right and he knew it," and she corrected the error. With her assignment finished, she expected to be sent back to the segregated West Computer group, but "to my surprise that never happened. Somehow the engineers forgot to return me. Instead, they just handed me the next set of calculations—and then the next . . . That's when I realized they needed me, Colored or a woman, or not."[28]

Johnson broke through many barriers—once, after being the primary contributor to a key report, her male coauthor helped her insist that she get credit. No women had previously been named an author on a report. In 2015, President Barack Obama awarded Johnson the Presidential Medal of Freedom for her contributions to the success of the space race.[29]

The West Area Computing group had a number of great group characteristics. It was highly talented, with outstanding leadership from women like those discussed here. Facing systematic segregation, its members certainly saw themselves not simply as underdogs but as victims of racism, with a lot to prove. They were highly collaborative and supportive, building each other's morale and confidence and teaching each other new skills (such as programming) to stay ahead of the pack. They were working on a series of technology challenge-based projects, facing daunting new challenges as rockets and space capsules demanded new applications. They were a group island, but their talents gave them contact with a few key supervisors who became a bridge for acceptance of their work. And working at NASA required connected science, where analytical mathematics translated into space flight.

ROBERT TAYLOR AND XEROX PARC

The computer scientist Robert Taylor, known to everyone as Bob, came out of ARPA, where he worked under J. C. R. Licklider on the creation of early personal computing and the internet. He was director of ARPA's Information Processing Techniques Office from 1965 to 1969, leaving to join Xerox Palo Alto Research Center (PARC), Xerox's new research center in the still-early days of Silicon Valley.[30] There, he founded the Computer Science Laboratory. He assigned himself four tasks: recruitment (one of his jobs at ARPA), structure, communication, and tools.

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Taylor considered himself a "connoisseur of talent," and at Xerox PARC, he adopted the ARPA creed "Choose people over projects" for his recruitment efforts. He looked for collaborative talent and purposely hired people he considered more talented than himself.

When it came to structure, Taylor saw it as "managing creativity." He aimed to "get really great people together and manage the social dynamic."[31] He required his team sign up for "the duration" of the mission, and the structure was nonpyramidal and flat, with no titles.

Task three was communication. Taylor felt that you can't force the direction of a high-powered group; it will move to whatever is interesting. Sharing information, though, was crucial. Taylor held, "No organization works beyond the size you can get all the principals together in a room and thrash out the issues before you go home."[32] So PARC became an intense learning environment. His team held a weekly meeting (based in part on his ARPA group's meetings), sitting on beanbag chairs in a large room, where they shared current research and took criticism of each facet from their peers around the room. Everyone was required to attend and stay until the end. Out of these sessions emerged a collective picture of the future of computing. Information was shared interactively in a social and personal setting—the meeting substituted for memos and paper.

Taylor insisted his team had to have the right tools—the fourth task he assigned himself. This meant access to the cutting-edge technology of the time, which he viewed as crucial to great groups. Xerox had a computer made by Scientific Data Systems that Taylor rejected as inadequate, so his team made its own, the MAXC. Taylor was able, after numerous battles, to persuade the "suits" at Xerox to let him move ahead and get the right tools to support their ongoing advances, even if they had to be constructed.

Taylor brought a near-religious zeal to his undertaking. He protected his PARC island; he "puts his body between Xerox and PARC."[33] Led by Alan Kay, who had been working on it before he came to PARC, a subgroup of the team produced the Dynabook, the first laptop, taking the idea from the Italian early Renaissance printer and humanist Aldus Manutius (1449–1515), who had argued that the ideal book would be portable and fit in a saddlebag. The group wanted to democratize learning with it, creating a book-size, interactive computer that a child could use.

The Alto, the most important and dynamic personal computer (PC) of the era, also emerged from the PARC team. It set the standard for all PCs to come. For it, a subgroup led by Butler Lampson created an interactive desktop with windows and the mouse (contributed by Doug Engelbart), making computing playful, not forbidding as it had been before the Alto. *Sesame Street*'s Cookie Monster was the first image on the machine. The PARC group saw a computer as something fun to use, not just a big calculator.

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PARC's advances in computing became standards for the industry: the graphical user interface (GUI), the Ethernet as a local-area computer network, fully formed object-oriented programming and the Smalltalk programming language, prototype-based programing, model-view controller software architecture, computer generated bitmap graphics, and, in the printing field, the laser printer.

While Taylor's PARC team created a famous computing island, Xerox failed to build them a bridge to the company mainland. Xerox's executives concentrated on the company's core capability, copying, and didn't grasp what PARC had made. The company failed to develop any of this; it violated the "island-bridge" rule of great groups by neglecting the bridge. It fell to Steve Jobs of Apple to commercialize these ideas. He bought rights from PARC and Xerox for a famous one-day visit in 1979, saw the amazing Alto technology, and built it into Apple's Macintosh. Jobs forced IBM to undertake its PC, and that, in turn, forced Microsoft to create Windows, building out the PARC vision. Jobs said, "Creativity is just connecting things. When you ask creative people how they did something, they feel a little guilty because they didn't really *do* it, they just *saw* something. It seemed obvious to them after a while. That's because they were able to connect experiences they had and synthesize new things."[34] This is an important definition of creativity, but it is also an explanation of what he did with the pictures he emerged with from his PARC visit.

While Jobs fulfilled the PARC dream for personal computing, Bob Taylor gets credit as a remarkable leader of a great group. His function "was as a central switching station, monitoring the flow of ideas and work and keeping both going as smoothly as possible. And although he wasn't a computer scientist and couldn't actually do the work himself, Taylor's intermediary role made him so indispensable that it was always clear who worked for whom. Taylor was the boss. They called it Taylor's lab."[35]

As one observer put it, "Without Taylor there would have been chaos."[36] Jack Goldman of Xerox, who created PARC, argued, "There are two ways of being creative. One can sing and dance. Or one can create an environment in which singers and dancers flourish."[37] Taylor was in the second category. At PARC, the team remembers it "as the time of their lives," and it was Taylor who built critical mass doing great things.[38]

Bennis and Biederman drew on Taylor's PARC team for a number of their great group characteristics. But the team didn't share every one of those characteristics. For instance, it lacked an enemy that would force them to ship—they were completely ahead of the game, and only after they made their advances did Jobs and Apple, IBM's PC, and Microsoft come into view, taking advantage of their advances. And Xerox famously failed to connect its PARC island with a bridge to decision-makers at Xerox headquarters that could implement their technologies.

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LOCKHEED'S SKUNK WORKS

Lockheed's "Skunk Works" provides an example of how a large firm can innovate and keep innovating. Founded by Kelly Johnson, a legendary aircraft designer, Skunk Works was named after a *Lil' Abner* cartoon in which strong beverages were brewed from mysterious ingredients. Lockheed's version was set up in a windowless two-story building next to two giant airport hangers in Burbank, California. Its team motto: "Be quick, be quiet, and be on time."

Under the leadership of Johnson, and later Ben Rich, the Skunk Works developed some of the most amazing aircraft of the twentieth century, including the P-38 long-range World War II fighter; the F-80 Shooting Star, the first US jet fighter; the U-2 spy plane; the F-104 Starfighter jet fighter (called "a missile with a man inside"); the highly maneuverable A-4 Skyhawk fighter; the SR-71 surveillance aircraft, the fastest (three times the speed of sound) and highest-flying aircraft ever; and the F-117, the first stealth aircraft.[39]

Johnson created a unique and largely secret group of outstanding aircraft engineers, who designed these remarkable aircraft. The core idea was to create a small, highly talented group of collaborative innovators within a larger company, protect and isolate it, but also give it access to decision-makers who could implement their projects. So the team followed the island-bridge model, completely separate from the rest of Lockheed in an isolated building, but with a bridge back to the mainland through strong ties that it maintained to top US air force, DOD, and Central Intelligence Agency (CIA) leaders.

Johnson, and later Rich, personally selected and hired top talent—a brilliant and dedicated group of engineers with crossover capabilities to fill a range of roles. The team was characterized by great camaraderie, as well as an intense commitment to their highly challenging projects. They faced a major Cold War mission and had an "enemy," the Soviet Union.

Its two most well-known leaders, Johnson and Rich (there have been others since), had very different leadership styles. Johnson was unbending and stubborn, while Rich saw himself as very much a team player. But both held the team to the highest and most demanding standards of innovation. Development of stealth technology provides a good example. Radar defenses had been making survival for military aircraft increasingly difficult. Denys Overholser, a Skunk Works mathematician and designer, discovered a Russian paper on "Edge Waves in Physical Diffraction." From it, he deduced the stealth concept, using it for the now-famous stealth diamond design to avoid radar detection. The Skunk Works team under Rich saw stealth as a means to transform air attack. Rich brought the concept to DARPA to support the project, and it evolved under Air Force development.

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Skunk Works used the technology challenge model, taking on tasks that required breakthroughs. To succeed, it developed some rules of its own, including don't reinvent what you don't have to and use available reliable technology whenever possible. These steps lowered development costs and cut the risk of creating new prototypes.

Skunk Works was able to innovate using the DOD's resources, with its willingness to undertake long-term investment and to accept risk to get to the technologies it wants. DARPA proved a critical Skunk Works ally for both the SR71 and stealth. Skunk Works stands as the model for how a traditional company can keep innovation moving through the company on a continuing basis by setting up an island.

As suggested here, Skunk Works had many of the Bennis-Biederman characteristics. There was great talent and great leadership, and the leaders hand-picked the talent. The team was definitely on a mission, and during the Cold War it had an enemy that spurred on their advances. The group focused intensely on their projects and followed the island-bridge model. They enjoyed high morale and camaraderie and prided themselves on meeting timing targets—they knew that they had to ship. They also operated under a technology challenge model and were flat and collaborative, with only two organizational levels. Skunk Works also exemplified the connected science approach, where research breakthroughs like stealth could be translated into amazing aircraft.

HERBERT BOYER, ROBERT SWANSON, AND THE ORIGINS OF BIOTECH

Herbert Boyer came from small Pennsylvania town, where his father was a miner and railroader.[40] He was big and played guard on his high school football team; it was his coach who got him interested in biology. He read about deoxyribonucleic acid (DNA), and his engagement with biology was signaled by the names of his Siamese cats: Watson and Crick. He studied at the University of Pittsburgh—which has a noted life sciences program—after high school, and then at Yale, taking time out to participate in the civil rights movement. He then joined the faculty at the University of California at San Francisco (UCSF) to pursue his interest in genetic research.

Robert Swanson, born in Brooklyn, New York, and raised in Florida, also came from a working-class background. His father was a maintenance crew chief for Eastern Airlines. His parents wanted to be sure he was the first in the family to go to college, pushing his studies and allowing him only one hour a week of television.

Swanson went to MIT, where he studied chemistry and then attended MIT's Sloan School of Management. While he did not become a scientist, unlike many businessmen he was never afraid of science—he understood and embraced it. The science processes that he learned also taught him to tackle things one at a time and manage his time well.

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After business school, Swanson headed to San Francisco for a job with Kleiner Perkins, the first of the West Coast venture capital (VC) firms. Tom Perkins had been a student of General Georges Doriot, the original thought leader who had created the East Coast VC model (see chapter 2). Eugene Kleiner had left William Shockley's semiconductor firm with Robert Noyce and Gordon Moore to form their own firm, Fairchild Semiconductor. While their VC firm, Kleiner Perkins, was busy pursuing computing, Swanson was reading about genetic engineering; the firm wasn't interested in his new territory, and his insistence on pursuing it got him fired. He was twenty-nine years old, had limited savings, and was out of work—but he saw the importance of the genetic engineering field.

To keep going, Swanson needed a scientist partner. He began cold-calling researchers working in genetics from an alphabetical list. He came to Boyer, a forty-year-old biochemistry and biophysics professor at UCSF who had codeveloped an ingenious technique for a new technology—recombinant DNA, which was based on splicing DNA from one organism into the genome of another.

The year was 1975, and the two men were about to change the drug industry forever. They met up at Boyer's lab and then went for beers at Churchill's Bar in San Francisco. By the end of a two-hour discussion, each had committed $500 to found a new company and they had sketched out a business plan.

Their interest in genetic engineering coincided with a period of public fears about it, highlighted in a 1969 bestselling technothriller by Michael Crichton called *The Andromeda Strain*, which is written as a report documenting a team of scientists investigating an extraterrestrial organism that causes an deadly outbreak in Arizona.[41] A 1971 film version of the story stoked those fears further.[42] By the mid-1970s, this compelled the National Institutes of Health (NIH) to halt its genetic engineering research.

Despite all this fear, Boyer and Swanson called their firm Genentech, for "genetic engineering technologies." A bronze statue of the two at Churchill's, striking their deal—Swanson in shirtsleeves and a tie and Boyer in bell-bottoms, with flowing, curly hair—was later placed in Genentech's headquarters.

Beyond their interest in genetic engineering more generally, what were the motivations for founding Genentech? Boyer saw that moving research to commercial applications was a way to "give something back" for all his years of government research funding. Swanson pictured himself at age eighty, looking back on his life, and concluded, "I'm not going to like myself for not having given this a shot."[43]

Swanson was first to see that you can create a company quickly around basic medical research breakthroughs. Genentech's project was to make synthetic human insulin from scratch chemicals—a synthetic DNA. They would need top scientific talent for the team.

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To help attracted talent, Swanson employed what was then an obscure approach. In those days, only managers owned equity in firms, but Swanson decided to offer stock options to scientific staff, believing that it would encourage longevity—which it did.

For his part, Boyer insisted that Genentech researchers continue to publish their work, which helped attract the best scientists who wanted peer recognition. This had other benefits, as Boyer explained: "Publishing our work helped validate the company in the eyes of potential customers and ensured we were doing good science by passing the muster with referees. It aided us with recruiting the best and the brightest because traditionally in the pharmaceutical industry trade secrecy trumped publication."[44]

Boyer and Swanson focused on finding the best people possible, attracting a group of promising somotostatin and genetics researchers who were attracted by the novel ideas, the publishing option, and the competition with other research groups.[45] They pushed the team very hard, asserting, "If you don't have more than enough on your plate you're not trying hard enough!"[46] Swanson's high sense of urgency instilled a culture where scientists worked very long hours and late nights for long periods of time. Using his contacts, Swanson got Kleiner Perkins to invest in two rounds of initial VC to get the enterprise going.

Genentech rented a corner of a South San Francisco warehouse. Researchers, clad in T-shirts and sneakers, worked fourteen-hour days and got their food from a vending machine. An Italian researcher sang opera to encourage the group.

Academic medicine was contemptuous of the new company, believing that corporate science could never clone a gene. The Genentech researchers—who saw themselves as winning underdogs—were in a competitive race with Harvard University's Wally Gilbert, a noted DNA researcher, and his team. They sported T-shirts emblazoned with "Clone or Die."

In August 1978, the group chemically synthesized the genes for insulin, beating Gilbert's group and another team in part because concerns over NIH research limits on genetic engineering (which didn't touch Genentech's research with synthetic DNA) had forced them to work in France and Britain. The next month, a splashy televised press conference announcing the breakthrough put Genentech on the map.

A significant factor in Genentech's ability to attract talent was their mission: a fight to keep people alive with breakthroughs. The atmosphere for the scientists at Genentech was open, unpretentious, relaxed, and respectful. Caring for staff was a priority despite the heavy workload and the pressure to win.

Genentech created the dynamic biotech model in the US, introducing the idea that a commercial model could speed breakthroughs better than academic research. Simply

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put, in the more vital commercial model, it was understood that "you have to ship." The model completely changed the relationship between universities and firms. Genentech played a critical role in eliminating the upstairs/downstairs (academic research/company research) relationship that had long characterized, and slowed, medical advances, enabling academically trained researchers to spend time in both companies and research labs.

CRAIG VENTER AND THE HUMAN GENOME

One of the most dramatic and public research races in medical history played out in the intense and bitter competition between a private-sector lab team led by Craig Venter and a group at the NIH and its network of supporting researchers led by Francis Collins. Their work tremendously accelerated the mapping of the human genome, a discovery that began to approach the secrets of human life.[47]

Here, Venter's leadership role is the emphasis; it shows a driven maverick leading an outstanding team that jump-started progress on mapping the genome at a private-sector lab that was able to move much more quickly than the typical pace of a research project with only government support. This point, which speaks to the value of public-private competition, requires examining more deeply the background and role of the team leader who made the competition happen.

Venter, born in 1946, grew up in a working-class neighborhood in Milbrae, California, just south of San Francisco; both his parents were former Marine sergeants. He was rebellious, became a competitive swimmer, and almost flunked out of high school. After graduation, he left home for southern California to surf off Newport Beach, living in a surf shack, playing, drinking, sporting long hair, and riding in hot rods.

With the Vietnam War expanding, he faced the threat of the draft, so he enlisted in the Navy. Despite his poor high school performance, he scored at the very top of the entry tests and opted for medic training—only finding out later that it is among the most dangerous military jobs. He got through boot camp and then worked in a California military hospital before being sent to a hospital in Da Nang, Vietnam, where he became the de facto head of the intensive care ward, to which the most seriously wounded were brought. During the infamous 1968 Tet offensive, the hospital was continually shelled.

It was in Da Nang that Venter came to the conclusion that there had been "a failure of our knowledge of medicine,"[48] and it offered only crude tools to save lives. Working at a village orphanage once a week and in the intensive care ward six days a week, twelve hours on and twelve hours off, but twenty-four hours a day when there were offensives,

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he became depressed by the death and suffering. One day, he decided to end his life and swam far into the Da Nang harbor, which was full of sharks. But once there, he changed his mind and swam back. He decided he wanted to become a physician instead.[49] His understanding of life-and-death consequences clearly fueled his driven nature. He had come a long way from his surfer days.

When he returned to California, Venter attended community college and then the University of California at San Diego (UCSD). He saw that medical research could save lives on a much greater scale than a medical doctor could do, so he changed his plan, earning a PhD at UCSD while undertaking significant research projects with his faculty mentor. From there, he went to the State University of New York (SUNY) at Buffalo to teach and do research, and then to NIH in 1984, where he worked on molecular biology.

Venter was not the typical academic researcher. There were few Vietnam vets at NIH, and few researchers quite so driven. He was not an easy fit into the NIH system of traditional academic research.

While at NIH, Venter heard about Lee Hood's early efforts at automated sequencing of the genome and requested that NIH purchase a sequencing machine. This was rejected, so he ended up buying one with funds from a confidential DOD project, and he used it to develop gene neurotransmitter sequencing data over a period of years.[50]

While NIH itself was largely ignoring genome sequencing, it turned out that the US Department of Energy (DOE) was very interested. DOE understood the power of supercomputing and its potential life sciences applications, and its work on sequencing genomes ultimately spurred NIH to catch up, and James Watson (of DNA double-helix fame) came to NIH to begin the Human Genome Project. Watson saw Venter's work and promptly announced at a congressional hearing a day later that NIH was ahead of the world in the field and Venter's lab would sequence the human genome.[51]

Venter, in effect, became an early bioinfomatics innovator because he saw the need for computing power and new algorithms for sequencing. He came up with a technique that he called "express sequencing tags (ESTs)" for short DNA sequence fragments (complementary DNA) and was able to process hundreds of new genes very quickly. On the advice of NIH's Technology Transfer Office, he moved to patent his results in NIH's name.

The controversial EST advance had disrupted Watson's planning and budget for slower, more in-depth analysis, and he turned on Venter at a 1991 congressional briefing, attacking him (and his EST advance) for trying to patent the genome.[52] In the ensuing outcry, NIH withdrew its patent application. The events drove Venter to leave NIH to set up his own nonprofit research institute funded by VC. The Institute for Genome Research (known as TIGR) was linked to a separate for-profit firm Human Genome

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Sciences, which backed TIGR and its research with funding to develop the genome sequencing results.

The race to sequence the human genome between Venter and NIH was on. The dynamism of a public-private competition, as with Genentech, became an important factor for speeding progress.

Venter's leadership qualities compelled most of his able NIH team, some twelve in all, to join him. He also added other talent. Subsequently, he met the researcher and Nobel Prize winner Hamilton Smith at a conference; Smith joined the group, Venter added computing experts to the team, and they and their colleagues led the "genome shotgun" method of sequencing genomic pieces as opposed to large clones.

NIH, with its own major government-funded genome project, became increasingly concerned that an independent lab with commercial company funding was getting ahead of it by processing breakthroughs; the biotech model was still relatively new, and NIH feared more broadly a profit motive entering medical research. NIH was also embarking on a more traditional approach to sequencing, with dozens of universities receiving traditional research awards to do the work, while Venter was assembling a highly organized, close-knit, expert team that viewed speed as paramount. Denying NIH's claim that they wanted to patent the genome for profit, and partly in response to the NIH concerns, the Venter group published an article in *Science* that made the EST and shotgun techniques clear to all researchers.[53]

In 1998, Venter broke off the support from VC, and his lab began to work with Perkin Elmer, an advanced technology company. They set up a new firm, Celera Genomics, and the group's efforts further accelerated, although they were spending only a fraction of the NIH project's costs. The Venter team also built what was then the world's third-largest supercomputer (1.5 terraflops in 1999) working with Compaq, to perform the genome shotgun process; DOE's smaller supercomputers were aiding the NIH genome project.

At NIH, Francis Collins replaced Watson to lead the genome project; he streamlined the NIH effort to resemble Venter's fast-moving project, slashing the number of universities involved to a working minimum. He had Eric Lander, a mathematician turned biology professor at MIT who led the Whitehead/MIT Center for Genome Research and understood computing, lead much of the computing side of the project—despite the fact that the NIH team had once criticized the computing approaches of Venter's group.

The competition spilled over into the public, and in the interest of science, pressure grew on the two men to stop making it a race. So they negotiated a simultaneous announcement of the completion of the human genome on the same day in 2000, three years before the NIH team was expected to finish, with Venter's team publishing in

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Science[54] and the NIH team in *Nature*.[55] *Time* magazine celebrated "Cracking the Code!" on its July 3, 2000, cover, describing the "bitter rivals" and their "historic feat that changes medicine forever." At the White House announcement in 2000, discussing the meaning of what they had done, Collins said, "We have caught the first glimpses of our instruction book, previously known only to God."[56]

Venter tied the discovery to his Vietnam experience: "In reconciling things with those men in Vietnam, we try to understand life. We try to explain what it meant . . . answered by rigorous scientific efforts."[57] As for Celera Genomics, it grew to a $14 billion market value but then crashed in the 2001 dotcom crash; Venter departed in 2002 and formed his own genomics research foundation, with most of his team joining him. Collins went on the lead NIH.

Venter and his team exemplify the power of the unreasonable and of insistent risk-takers. It is a story of the importance to the team of leadership. "Ideas are a dime a dozen," Venter later told an interviewer. "We'd have ten times the level of innovation if people were less afraid to pursue them," adding that "it takes brilliance to know how to execute, and it takes courage of conviction to be willing to do it."[58]

Venter inspired strong loyalty, with many of his team sticking with him throughout, beginning from when they first started working with him at NIH. Venter was a unique leader, with a personality that helped spark a critical advance in medical research. His driven leadership qualities were critical to the human genome advances. Nevertheless, he depended on a highly collaborative and able team for the accomplishments.

This, then, is a story—in a more accentuated way than the examples earlier in this chapter—of the dynamic relationship between leader and team. Many of the "great group" characteristics apply to this instance: great groups and great leaders create each other; the group was highly talented; their members saw themselves as on a very serious mission and as winning underdogs; and the team operated with the intensive zeal of converts. They were egged on by attacks from their competitor NIH group, so they faced an enemy. The group operated on an island, protected from outside forces by Venter, but thanks to Venter's ties to venture and corporate funding, they had a bridge back to the mainland to help them get their research completed and released.

Part of Venter's leadership story, then, is how he steered the group into a highly competitive race with NIH-funded researchers. They were also able to use the latest sequencing equipment and built their own supercomputer, so they had the cutting-edge technology that they required. The group used the challenge model to meet their goal of sequencing the human genome. They were flat and collaborative and used connected science, from basic advances in genomics and computing processes, to sequence and publish the genome.

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DIGITAL EQUIPMENT CORPORATION

The last of our case studies is different. While the others are about success, Digital Equipment Corporation (DEC) failed to keep innovating after its initial innovation. The DEC story contains lessons about great groups and the challenge of making them enduring rather than transitory.

What happens after the innovation moment? How do great groups fail? How do you keep the group alive?

As Edgar Schein has written, DEC was, from the outset, less a management culture than a technological vision.[59] The company had many of the characteristics of great groups. It was initially relatively flat, collaborative, antihierarchy, and featured a diversity of talent. It had open communications and operated through "functional familiarity"—shared experience at a face-to-face level. It focused on empowered "problem solving" and "doing the right thing." Rather than being told what to do, employees were relied on to evaluate situations, understand problems, and "do the right thing" to resolve them.

Initially, these characteristics were advantages. Later, they caused problems. The company was highly reliant on individual initiative, but its leaders had limited large-scale management experience.

The early DEC technology and culture were built on the company's development of the minicomputer, the next stage of advance past mainframe computing. Its founder and chief executive officer (CEO), Ken Olsen, came out of MIT and had worked on the SAGE computer and at Lincoln Lab. He was able to obtain early-stage VC funding from General Doriot, the founder of US entrepreneurship education. It was Olsen who established the early DEC culture of self-empowered innovation and "doing the right thing." By 1987, DEC was the second-largest computer company in the US and on a track to pass IBM in industry leadership.

There had been three periods of computing advances during DEC's span. The first, led by IBM, lasted from 1951 to 1965 and featured mainframes and batch processing. The second, from 1965 to 1981, featured time-shared computing and minicomputers from companies such as DEC, Hewlett-Packard, and Wang; DEC helped lead this period. The third period began in 1981 and featured desktops, personal computing, laptops, workstations, servers, and handheld devices; Apple, Microsoft, Cisco, and Oracle were leaders during this period—which is when the DEC bubble burst, a process that unfolded between 1988 and 1992.

While it had led in minicomputers, DEC simply missed the move to microcomputers, desktops, and servers. Its initial innovation culture couldn't respond to that next disruptive innovation shift. To be more specific, DEC arose in the *creation stage,* as mainframe

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shifted into minicomputers, but it missed what can be called the *dominant design phase* in the third period, when desktops, laptops, and handhelds evolved.

DEC's downfall was in the interaction of its culture, organizational structure, and technology. When DEC grew very fast and became a much larger firm, its leadership team lost its functional familiarity. It could no longer depend on face-to-face relationships and personal knowledge; the bureaucracy had become too large. DEC's concepts of doing the right thing and individual initiative also faded when the company shifted from family size to a large company. The organizational structure shifted as well, to distributed leadership subunits; these had their own subcultures, which made a company-wide strategic focus more difficult. Meanwhile, as DEC's core technology evolved, the company lacked the culture and organizational structure to shift toward the new technology advances. Founded around a great group culture, DEC had created a remarkable series of innovative minicomputers. But the intimacy of the great group faded as it became a major corporation, and it missed the next stage to technology advances.

The lesson here is that it is crucial for a great group to evolve as it scales up, adjusting its mix of culture, organization, and technology. That's what Lockheed's Skunk Works did, and it provides an example of how a large company can keep innovating by creating a separate island within itself, oriented to ongoing innovation. DEC was unsuccessful at that.

It turns out that great groups, when formed within larger companies, continue to thrive by virtue of some separation from the larger entities' growth and evolution.

RULES FOR BUILDING GREAT GROUPS TODAY

The lessons that emerge from these great groups, along with the one failure described here, reinforce the characteristics that Bennis and Biederman articulated. These characteristics also suggest a series of rules for creating great groups today. This can't be a complete list of great group rules since the chemistry of every group will vary. But these are the rules that seem to stand out from the case studies.

Great groups must be highly collaborative and have the right people with the right skills doing the right jobs. Their culture tends to be flat, nonhierarchical, and often democratic; everyone feels free to pitch in on making decisions. They often occupy a space where technology and earlier-stage research interact, moving from basic to applied and vice versa. So they need that mix in the group—theorists and tinkerers and experimentalists that mind-share. Overall, the group needs to be highly talented, and they get the right people doing the right tasks. The leaders must collect great talent, not just good talent, and they must create a dynamic relationship between their leadership and the

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motivation of the team. The group also needs to be networked to the best thinking in the fields that they are working in.

Great groups must apply a technology challenge model. They must set out a vision at the outset that entails a significant technical challenge, turning a work project into a *mission*. In meeting the challenge, they use connected science, often finding roots in fundamental science but applying breakthrough applications that stretch across basic, applied, prototype, and development stages.

Great groups require great leaders. Great groups leaders have different leadership styles, as we have explored, but great groups always need outstanding leaders. Equally, the great leaders need the great group. The leaders must get a series of steps right; they play a central role with respect to certain key rules. As Bob Taylor of ARPA, and then of Xerox PARC, indicated, leaders have several vital tasks: *recruitment*, assembling great talent for the group; *structure*, getting the internal organization right so each member can be creative; *communication*, so there is constant idea trading; and *tools*, ensuring the best research equipment. Leaders also play a key role in steering around and through competitors, as Venter showed in the human genome effort and Swanson and Boyer demonstrated at Genentech. Sometimes great group leaders have to break out of the box to achieve the mission, as Venter did by obtaining private-sector funding.

Leadership styles, as noted, can vary. Innovators can be seen by others as unreasonable troublemakers. As previously noted, someone once characterized J. Robert Oppenheimer's role in the Manhattan Project to that of a bee spreading pollen. Robert Taylor at Xerox PARC, working on desktop computing, saw himself as a network connector, a central processing unit. Edison's leadership style was more in the mode of a nineteenth-century disciplinarian; Steve Jobs on the Mac project at Apple pushed hard and could be dominating and acerbic. Craig Venter is a particularly clear example: he was a maverick, driven and devoted to taking on big challenges and dealing with competition; he also garnered great loyalty that built an outstanding team. He came from a very different background than other life scientists and launched an assault, both verbal and scientific, on the competitor, the established Human Genome Project at NIH.

Tyranny, though, can ruin a group. William Shockley's ego and authoritarian demands not only drove Walter Brattain and John Bardeen out of the Bell Labs transistor group, but later drove Robert Noyce, Gordon Moore, and the entire group of semiconductor leaders out of Shockley Semiconductor to found their own company, which later developed the integrated circuit and created Intel.

The groups must ship. Leaders play a vital role in getting the team to "ship," as the work of Steve Jobs at Apple, for example, shows—but the work of Taylor at PARC does not.

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Great groups are not doing academic research; they must set real deadlines and take on their competition.

Great groups must have the right tools to work with. The site where a group works doesn't have to be elegant—the Genentech team worked in a South San Francisco warehouse—but cutting-edge tools typically must surround the group. Making sure of that is an important group leader task.

Communication and information flow are critical to great groups, and the leaders play a role in ensuring both. Great groups require continuous information exchange. Leaders must create an atmosphere for continuous info flow so that collective ideas develop. A continuous learning environment is key for a group's combined talents to come to the forefront. Many groups find the project team needs to fit in a single room for group communication; networking often occurs face to face. Each group member needs to be in the know and contribute to the others. At Xerox PARC, the entire group filled a room and sat on beanbags during intense weekly debates about progress; by contrast, the leaders of the project at Los Alamos, for security reasons, never told the large group of engineers who had been brought to do calculations what the project was about, and their progress was desultory. When the noted physicist Richard Feynman arrived to turn the group around, he insisted that the engineers be told about the mission—and once that happened, far greater progress was made.

A great group needs focus and camaraderie. The group must intensely focus on its technology challenge and set aside everything else. Groups also need high morale and to have fun—they need to play with new ideas as well as to apply them. The atmosphere needs to foster creativity and risk-taking. Veterans of great groups, for all their intensity, often feel like they were having the time of their lives. Again, group leaders play an important role in establishing this structure.

Great groups need to be on an island, but also require a bridge. Although to make progress great groups need to be on a protected island away from an interfering bureaucracy, they also need a connection to decision-makers who can help them implement their technology advances. Edison was able to bring his advances in lighting and an electrical system to the financier J. P. Morgan. Alfred Loomis at the Rad Lab needed to be able to reach Secretary of War Henry Stimson, his cousin, who could reach President Franklin Delano Roosevelt. And Vannevar Bush was able to apply his authority through his ties to Harry Hopkins and Roosevelt. Venter and Swanson were able to ensure corporate support for their projects. In contrast, Robert Taylor's group at Xerox PARC was too isolated to have an effective voice at corporate headquarters, and DEC under Ken Olsen failed to keep innovating in part because after its minicomputer innovations, it failed to set up protected project teams that could become great groups for subsequent

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innovations. Group leaders, then, play a significant role in both protecting the island and in erecting the bridges.

Great groups need clear competitors; it also helps if they have an enemy. Venter's team at Celera was competing with Francis Collins and Eric Lander of the NIH's genome project. Apple was competing with IBM. The Rad Lab pressed its radar advances with the outcome of World War II in the balance. The Los Alamos scientists were competing with Nazi Germany, frantic that a former physics colleague, Werner Heisenberg, would be first to the atomic bomb and the Germans would win the war. All these groups used competition to inspire a religious-type zeal in pursuing their technologies. Leaders play a role in managing this competition, as exemplified by Venter and Oppenheimer.

In sum, many of the organizational features of great groups are common across groups—and thus suggest these rules. A venture capitalist once mentioned to me that he looks for these same kinds of group characteristics every time he funds a start-up.

In the end, innovation is the work of amazingly talented people, and the great groups in which they most often work make all the difference.

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6 THE DARPA MODEL FOR INNOVATION

We glimpsed the defense-driven innovation system in earlier chapters, in the stories of interchangeable machine-made parts, the role of the Rad Lab in developing radar and electronics, the development of real-time computing, and through some of the great groups. This defense innovation system really began to emerge at scale in the US during World War II and in the postwar years.

The US Department of Defense (DOD) played a critical role in the evolution of the major innovation waves of the second half of the twentieth century: aviation, nuclear power, electronics, space, computing (including mainframe, semiconductors, software, and supercomputing).[1] The Defense Advanced Research Projects Agency (DARPA) proved a particularly critical new innovation model, one that would have far-reaching consequences for innovation and the US economy.

DARPA was formed in 1958 as the Advanced Research Projects Agency (ARPA; again, ARPA and DARPA are used interchangeably in this book) by President Dwight D. Eisenhower to provide more unified defense research and development capability in light of the separate, stovepiped military services' space programs that were partially responsible for the Sputnik failure of the US. DARPA became a unique entity, aimed at both avoiding and creating "technology surprise." The agency is especially famous for playing critical roles in the information technology (IT) revolution.

The DARPA model for organizing innovation, now copied by three other US agencies, is distinct from other innovation agencies around the world in its rejection of the "pipeline" and technology "handoff" approaches that most others use. As an innovation organization, DARPA takes responsibility for bringing about technological breakthroughs and nurturing them toward delivering final products. To do this effectively, the agency

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has developed a number of specific organizational practices that have led to its playing a critical role in technology advances such as the internet; wireless transmission advances; microelectromechanical systems; microprocessor advances; personal computing; supercomputing; the global positioning system (GPS); lightweight collaborative robotics; revolutionary new military equipment (including precision strike and stealth technologies, as well as drones); synthetic biology; computer simulations and gaming for training; driverless cars; and the development of messenger ribonucleic acid (mRNA).[2]

The development of personal computing and the internet, led by J. C. R. Licklider, illustrates DARPA's role at its most productive.

J. C. R. LICKLIDER, PERSONAL COMPUTING, AND THE INTERNET

The development of personal computing (i.e., desktop computing; microcomputing) relied on the DOD playing a critical role, initially direct and later less direct.

In 1960, J. C. R. Licklider wrote a seminal article that envisioned much of what was to come.[3] He was a professor of psychology at the Massachusetts Institute of Technology (MIT) who was also an acoustics engineer and early computing thinker, and he was frustrated by the arm's-length, hands-off nature of the batch-processing, card-spitting, "big calculator" model of mainframe computing.

With remarkable clarity, Licklider's article portrayed the computer as an embodiment of what he called "man-computer symbiosis" (the article's title). He saw computers not as *dominating* people, but rather interacting on a contributing and collaborative continuum with people. He foresaw graphics-rich personal workstations, time sharing and computer-aided collaboration, networks and an online community, online libraries of the world's knowledge and information with instant retrieval and universal access, and computer languages that would enable a new digital medium of expression. He also saw the evolution of information science into a new science of computing as a significant new scientific field that would lead to new ways to portray and thus understand complex data, and the shifting of rote work and work preparation to computers.[4] He uniquely saw computers as potentially fun, exciting, and a joy to play with.

In 1962, Licklider became the first director of DARPA's Information Processing Techniques Office (IPTO). He was the critical initiator of key aspects of the information revolution.[5] He created a new office that linked behavior and computing to solve what DARPA was thinking of as "command and control" challenges."[6] President John F. Kennedy and Secretary of Defense Robert S. McNamara were fresh from dangerous communications breakdowns during the Cuban missile crisis, so improving command and control became a presidential mission for DARPA. Although Licklider initially

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wondered what his own new vision of computing had to do with command and control, DARPA director Jack Molina persuaded him that they converged.

This was the rarest of innovation moments: the technology visionary was given the resources to become the technology implementer.

An early task was to address time-sharing. Computers at the time were very expensive mainframes; ideas for minicomputers were just starting to emerge from Digital Equipment Corporation (DEC) and a few other firms. Time-sharing allowed multiple groups of users some slivers of a central computer's processing time apiece—an early version of interactive computing, with numerous users operating off a central utility. DARPA spawned Project MAC at MIT, where programming for time-sharing enabled the first online community, with online bulletin boards, email, sharing of software ("freeware"), and early computer games—and it also enabled some hackers.[7]

Innovation is, ultimately, intensely personal and face to face, and at the level of complex technology it requires "great groups" (see chapter 5). Under Licklider, DARPA selected and funded a number of great groups involved in innovation.[8] These were breathtakingly talented research teams from research institutions around the country that would, over time, field personal computing. Groups like these require support from institutions within ecosystems of innovation, and DARPA was uniquely able to support great groups (often operating as a great group itself), while also operating at the institutional level to evolve the innovations from the groups that it supported.[9]

Doug Englebart's team at Stanford Research Institute (SRI) was one of DARPA's proudest "great group" examples; the group developed the mouse, onscreen windows, hypertext, full-screen word processing, collaborative real-time editing, graphics, and video conferencing, and demonstrated these innovations at a 1968 DARPA-sponsored computer conference in what has come to be called "The Mother of All Demos."[10] SRI managers thought that Engelbart was flaky, but Licklider supported him from the beginning of his DARPA IPTO tenure.

Bob Taylor, who assembled the great group at Xerox Palo Alto Research Center (PARC) described in chapter 5, had been a Licklider team member at DARPA before doing so, and later succeeded Licklider as IPTO director. Some of the PARC group's ideas were picked up from Engelbart and from other DARPA projects, and they helped lead to the creation of the first personal computer (PC), the Alto.[11] Although Xerox famously failed to commercialize it,[12] Steve Jobs at Apple saw the Alto model and its concepts and created the Mac.

The point here is that while DARPA itself did not *create* the PC, the agency fostered and supported the great groups that systematically erected its foundations. DARPA clearly played a primary role in the creation of the internet, which was indispensable to scaling personal computing. Licklider once again was present at the creation. In an

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April 1963 DARPA memo to the research community that he was funding, addressed to "the members and affiliates of the Intergalactic Computer Network,"[13] he outlined the need to connect them all through their computers to form a single network that would bridge computers across the continent. He wanted an electronic commons as "the main and essential medium of informational interaction for government, institutions, corporations and individuals."[14] It would support electronic commerce, banking, digital libraries, the "dissemination of information in your field of specialization, announcement of cultural, sport, and entertainment events" and on and on and on.[15]

DARPA selected BBN, a Cambridge-based MIT spin-off (Licklider had started its computer wing), with a team under Frank Heart, to put up ARPANET in 1969. It reached into the growing number of university computer science departments that DARPA funding had initiated, and a user community began growing to scale as new internet features were added, building on the foundational Transmission Control Protocol/Internet Protocol (TCP/IP) contributed by the DARPA researchers Bob Kahn and Vint Cerf.[16] True scaling was enabled when DARPA shrewdly spun off ARPANET into NSFnet, with the growth of the internet backbone guided by critical decisions by Steve Wolff, NSF's manager for the internet. He and his colleagues helped evolve the "internet service provider" commercial model, multiply the backbone, and finally created NSFnet in 1995.[17] Then Tim Berners-Lee combined hypertext and browsing into the World Wide Web,[18] and, as they say, the rest is history.

When Licklider died in 1990, the revolution first launched by "Lick's kids" to make computing personal was in full force, and IT became an economic innovation wave, leading toward the close of the twentieth century to one of the strongest, sustained periods of growth in US history.

There is an important lesson about innovation systems from DARPA's role in these advances. The IT revolution led by DOD agencies did not evolve from curiosity-driven research, but rather from systematically addressing—at every stage of the innovation process—a series of carefully posed technology challenges in several related sectors. This clearly led to very significant results, and organizing innovation advances around technology challenges stands as a model today.

DARPA'S ROLE IN THE PC REVOLUTION

Licklider had the vision of personal computing, but that story is not the one that we typically hear. The widely accepted version of the PC revolution is a story of the triumph of American individualism—that it happened thanks to risk-taking entrepreneurs working in garages, empowered by a free market. Bill Gates, the cofounder of Microsoft, put it this

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way in 1988: "The PC industry is leading our nation's economy into the 21st century. . . . There isn't an industry in America that is more creative, more alive, and more competitive. And the amazing thing is all this happened without any government involvement."[19] Let's get to the bottom of this.

The PC embodied a system of technologies that were personal and transformed the thrust of computing away from the impersonal mainframe stream of computing. The PC's origins are typically traced from Xerox PARC (as noted in chapter 5), then to Apple, and then to Microsoft. But the actual history begins earlier.

Glenn Fong has examined the deep role of the DOD, and DARPA in particular, and taken the usual business story apart.[20] His analysis picks up after Licklider's initial visionary role. He notes that personal computing had its origins in the "human computer interface," a vision that Licklider pioneered with his work on "man-machine symbiosis," as noted previously. Much came out of the time-sharing effort that Licklider was part of, enabling individual users to have time on mainframe computers. Then three evolving streams in computing came together: engineering and computer science created advances in computer graphics, operating systems, programming languages, and software development; behavioral science disciplines—communication theory, linguistics, learning theory, and cognitive psychology—assisted, with Licklider providing much of the thinking; and graphics and industrial design, along with ergonomics, also contributed.

Fong writes that "keyboard commands; pointing devices; touch screens and other display technologies; voice, handwriting, and gesture recognition; eye movement tracking; biological and psychic sensing; computer speech; graphical user interfaces (GUIs); user navigation and menu selection tools; windows environments; and desktop metaphors"[21] were the implementing technologies and techniques. All this led to the human computer interface behind personal computing. Xerox PARC, building on DARPA research including work by SRI, pioneered many of these elements in its development of its Alto desktop computer in 1973.

How did they emigrate to industry from PARC? In December 1979, Steve Jobs and his team made a famous visit to PARC and saw these technologies at work—and then they developed their own versions. Fong notes that Apple, first in its Lisa computer and then in its Mac, took from the PARC visit the desktop metaphor, pop-up menus, overlapping windows, scroll bars, the GUI, and the mouse.

It wasn't just ideas that moved from PARC, however; it was also people who could effectuate those ideas. A number of key PARC staff went to Apple, including Alan Kay, the evangelist at PARC for the Dynabook, which later became the laptop; and Larry Tessler, who worked on the Apple versions of the Alto user interface and mouse.

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For his part, Bill Gates visited PARC in 1980 and had an Alto demonstration. He visited Apple the next year and then obtained Mac prototypes in 1982. Microsoft developed its Windows software in 1985, informed by PARC's GUI for the Alto as well as Apple's GUI for its Mac.

When Apple later sued Microsoft for copying its Mac operating system and user interface, Microsoft's defense, in essence, was that both companies had taken their technology from PARC.[22] Charles Simonyi, PARC's leading programmer who developed a number of its "killer apps," had gone to Microsoft to become head of program development. Scott McGregor, who led PARC's windowing system, went on to lead Microsoft's Windows development. A number of other PARC leading lights also joined Microsoft.

The PARC ideas spread from its Palo Alto lab as its staffers moved to other companies as well. PARC was like a *good* virus.

We've reviewed how PARC's ideas spread into computing companies, but let's go back one step further, to PARC's ancestry. It reaches straight back to DARPA.

When Licklider left DARPA in 1964, he named Ivan Sutherland to replace him as head of IPTO. Sutherland's 1962 PhD project at MIT—with research support from the Army, Navy, and Air Force—had been Sketchpad, the first-ever computer graphics program, which allowed the user to draw on the screen interactively. To make the drawing, it used a "light-pen" pointing device, a predecessor of the mouse, which could also drag and drop images. The program also used a monitor: the results would show up on the screen, which meant no waiting for a printout. And Sketchpad had a rudimentary windows system, with the screen split to create two work areas. It was a major breakthrough. Following in Licklider's footsteps at DARPA, Sutherland funded university groups to exploit all these advances before they were picked up at PARC.

Robert Taylor at DARPA's IPTO shared Licklider's vision for what Licklider had called an "intergalactic network" and worked to shift the concept from time-sharing to a decentralized packet-switching network, the aforementioned ARPANET, which became today's internet. The network design for ARPANET was undertaken by Taylor, and its construction began under Taylor's successor at IPTO, Lawrence Roberts. Licklider and Taylor also wrote a 1968 paper that envisioned a computer for each individual user; it would have a large television monitor, a keyboard, and "electronic pointer controllers called 'mice' [that could] control the movements of a tracking pointer on the TV screen."[23]

Taylor took all these ideas, went to PARC, and then built a team that included a number of former DARPA-funded computer researchers (an "ARPA Army," in the parlance of the time) to join him. Licklider and his successors at DARPA had been creating the early computer science departments, funding teams of highly creative research groups at select universities that included University of California at Berkeley, MIT, Stanford, Carnegie

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Mellon, University of Illinois, University of California at Los Angeles, and University of Utah. Taylor drew PARC researchers from many of these groups, including Charles Simonyi and Larry Tessler from Stanford and Charles Thacker and Butler Lampson from Berkeley, all leading computer scientists supported by DARPA. Doug Engelbart, inspired by Licklider and Sutherland's Sketchpad and supported by DARPA at SRI, joined PARC, worked on the Alto, and developed the mouse. Numerous graduate students came from the DARPA-supported schools as well. When the Alto failed to emerge from Xerox, these researchers and other PARC designers moved to Apple and Microsoft.

Of course, PARC was not the only game in town. As Fong showed, the "who's who" of early computer science at the universities backed by DARPA in turn sponsored computing breakthroughs or emigrated to found or join companies such as Pixar, Atari, Silicon Graphics, Netscape, Adobe, 3Com, and Sun. In other words, DARPA created an amazing "thinking community" at a growing scale, which in turn spawned the ideas and then the companies behind the human computer interface movement and its product, personal computing. An economic surge—the IT innovation wave—followed by the 1990s.

DARPA IN THE CONTEXT OF INNOVATION POLICY

DARPA was a Cold War creation, formed in response to a technological crisis. Its operating practices began without any significant inspiration from innovation theorists or growth economists; its early program officers learned by doing. It is only relatively recently—some sixty years later—that innovation theory is catching up and theorizing about where an agency like DARPA fits.[24]

In the US literature on science, technology, and innovation policy, the DARPA model has come to be seen as occupying a unique place in the context of an established policy foundation. How does DARPA fit in to that? Let's briefly recap some of that literature discussed in earlier chapters.

The economic foundation for the innovation policy field is Robert Solow's work positing technological and related innovation as the dominant causative factor in growth.[25] Paul Romer and other new growth theorists argued the importance of technological learning as the underpinning for Solow's technological advance theory.[26] These two strands led to an understanding of basic, underlying innovation factors, both *direct* and *indirect*.

The direct factors include support for research and development (R&D) and follow-on technological advances, and support for Romer's concept of human capital engaged in research, which lay behind that system. Richard Nelson, in turn, showed the importance of understanding comparative innovation systems—of assessing the actors in an innovation system and their comparative strengths.[27] Then there is a third direct innovation

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factor, innovation organization—a connected system of innovation institutions and organizations.

These factors, particularly the organizational factor, shaped the US innovation system. DARPA exemplifies a unique innovation organization model within that innovation system that deserves explication.

In the postwar period, Vannevar Bush's highly influential "pipeline model" for the postwar organization of US R&D agencies was a "technology push" or "technology supply" model, with government support for initial research, but only a very limited government role in moving resulting advances (particularly radical or breakthrough innovations) toward the marketplace.[28] Development and the later stages of innovation were left to private industry. Donald Stokes and others subsequently sharply critiqued Bush's pipeline model as inherently disconnected, separating the government-supported research actors from the industry development actors, with few means for technology handoffs between them.[29]

Lewis Branscomb and Phillip Auerswald articulated the "valley of death" critique: the disconnect in the US system between research and later-stage development led to system failures in the commercialization of research results.[30] This concern has been the major focus of US science and technology policy literature for the past twenty years, with discussions of bridging solutions across this valley.

The DARPA model was a departure from Bush's pipeline. DARPA aimed at creating technological solutions to major innovation challenges. It went beyond Stokes's "use-inspired" research. Yes, it would embrace basic research in the search for breakthroughs, but it focused on actual innovations and bringing breakthroughs to implementation. In effect, DARPA itself was a bridging mechanism, connecting the research side of the valley of death with the development side.

THE EXTENDED PIPELINE INNOVATION MODEL

Of course, the pipeline model is not the only US innovation system model. There is the extended pipeline model, exemplified by the DOD's separate and parallel innovation system and within which DARPA sits. DOD developed the model to address Cold War technological demands, which would not tolerate a disconnected model.[31] In this model, the government is *deeply* connected, with DOD R&D organizations (as well as certain US Department of Agriculture agencies) support moving innovations through every innovation stage. This means support not only for front-end R&D, but also for each successive back-end stage, from advanced prototype to test bed demonstration and often to initial market creation, where DOD will buy the initial products.[32] It is a

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mission-oriented innovation approach, organized not simply around R&D but toward its actual implementation.[33]

Most of the major innovation waves since the end of World War II have emerged from this system.[34] The extended pipeline facilitates bridging the valley of death between advanced research and implemented technology. The change agent includes the governmental entity seeking the advance; DARPA is positioned squarely within this model, and it was, for example, a critical change agent for computing and the internet, as discussed previously. In general, US innovation organizations in recent decades have tended to stretch their capabilities further down this innovation pipeline.[35]

Innovation policy theorists have long analyzed the gap between the front end of the innovation system—the research side, typically supported by government R&D through university research—and the back end, the late-stage development through implementation phases, typically a private-sector domain. Numerous bridging mechanisms have evolved, often with government support, to resolve this structural problem. As Philip Shapira and Jan Youtie have noted, resolving it requires technology diffusion approaches and a range of institutional intermediaries.[36]

DARPA is not a traditional basic research agency. It also functions as a public-sector intermediary, working to nurture new technologies from breakthrough stages through applied research and initial development, and then to pass the technologies to entities that will move them into implementation. As an intermediary, it also operates as a change agent.

DARPA is clearly a mainstay of the extended pipeline model. But it is also important to note that that agency has been able to succeed because the US already had a rich and complex publicly funded science and technology system, including federal labs, university-based labs, basic research agencies, and a network of private-sector R&D labs, including, of course, Bell Labs (although many of them are now gone).[37] DARPA could cherry-pick the most promising technologists because there were many from which to choose. In turn, the agency helped produce more experts—its support for the early computer science departments, for example, deeply benefited the emergence of the field in general.

THE DARPA MODEL: BEYOND THE EXTENDED PIPELINE

Beyond its place within the sweep of the extended pipeline model, DARPA has also developed features that have enabled it to act as a unique innovation organization agency despite being part of the complex, often conservative, 200-year-old defense legacy sector.

There is an obvious rule here: if there's no innovation system, then there's no innovation. For its development, innovation requires an understanding of the overall system,

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but the first problem concerns the *earlier* stages of the innovation system in which innovations originate. Overcoming structural barriers to innovation and creating linkages between the innovation actors come at later stages of the innovation process, when change agents play a role and where ideas move to implementation. The first issue to tackle, however, is how to initiate innovation, whether in legacy or frontier sectors, at the front end of the innovation system—the research, development, prototyping, and early demonstration stages.

In many ways, DARPA directly inherited the *connected science and technology* (linking science research to implementation stages) and *technology challenge* (pursuing major mission technology challenges) organization models of the Rad Lab (for radar) and Los Alamos projects (for atomic weapons) erected by Vannevar Bush, Alfred Loomis, and J. Robert Oppenheimer in World War II (discussed in chapters 3 and 5).[38] Building on the Rad Lab example, DARPA built a deeply collaborative, flat, close-knit, talented, participatory, and flexible system, oriented toward breakthrough, radical innovation. Its challenge model for R&D linked fundamental and applied, creating connected science and technology and joining research, development, prototyping, and access to initial production. In other words, it followed a full *innovation* path, not just a discovery or invention path.

Strengthening the front end of the innovation system requires an innovation capability analysis of the research, development, prototyping, and early demonstration elements, as well as the institutions that support them.[39] Is the system capable of generating the innovations required to bring change to complex and legacy sectors? System improvements may be called for. Since the front end of innovation is typically backed, initially, by support through pipeline or extended pipeline models, we must first consider these and their application to the optimal innovation organization approach. A series of factors for consideration in this first step and the application of each to DARPA are discussed next.

FORM A CONNECTED INNOVATION INSTITUTION

If R&D is not being conducted at an adequate scale by teams of talented researchers, innovations will not emerge. But talent alone is not enough—talent must be operating within institutional mechanisms capable of moving technology advances from idea to innovation. Critical innovation institutions represent the space where research and talent combine, where the meeting between science and technology is best organized.

Arguably, there are science and technology institutions that can introduce not simply inventions and applications, but significant elements of *entire* innovation systems.[40] This is where DARPA, with its history of attracting outstanding research talent and spurring remarkable technology advances, takes center stage.[41] In promoting innovation, it has

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long supported frontier sectors, such as through its role in the IT wave and, within the defense legacy sector, through its role in defense advances such as precision strike and unmanned aerial vehicles. As the most successful US R&D agency operating in the innovation space, and because it represents more of a "connected science and technology" approach than other agencies, our initial focus is on lessons that can be learned from the characteristics of the DARPA model.

However, innovation not only requires a process of creating connected science and challenges at the institutional level, but also must operate at the personal level. Individuals are the innovators, not the institutions where talent and R&D come together per se. Innovation, because it requires more linkages than the earlier stages of discovery and invention, requires great groups of the sort discussed in chapter 5.[42] Unlike other federal R&D agencies, DARPA has operated at both the institutional and personal levels, fostering great groups. DARPA became a bridge organization connecting the institutional and individual organizational elements.[43]

UNDERTAKE TECHNOLOGY VISIONING

At the heart of DARPA is what has been called a "technology visioning process."[44] It uses a right–left research model: if early-stage research is on the left of an innovation pipeline and implementation on the right, DARPA's program managers contemplate the technology breakthroughs that they seek to have emerge from the right end of the innovation pipeline, and then go back to the left side of the pipeline to look for proposals for the breakthrough research that will get them there. DARPA also employs a technology challenge-based research model, seeking research advances that will meet significant technology challenges. It looks for revolutionary breakthroughs that could be transformative of a technology sector.

All these elements go into a process in which agency program managers develop a vision of a technology advance that could be transformative and then work backward to understand the sequence of R&D advances required to get there. If these appear within the range of accomplishment, DARPA has processes that allow rapid project approvals by agency directors. This technology visioning process is very different from the "stage gate" process in industry, with its step-by-step selection of technology options and in which budgets and the potential for market gain are factors used to weed out incremental advances not to pursue.[45]

DARPA's visioning process also differs from how other federal R&D organizations work; they place greater emphasis on research for the sake of discovery, not technology implementation. When attempting to bring innovation into a complex, established legacy sector, such as defense, the visioning process may be particularly suitable.

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ADOPT R&D BEST PRACTICES

Other DARPA practices enhance its ability to operate at both the institutional and personal innovation organization levels. The following list is largely drawn from DARPA's own descriptions:[46]

- *Maintain a small and flexible organization.* DARPA has only 100 program managers and office directors; the agency was once described as "100 geniuses connected by a travel agent."[47]
- *Keep the organization flat.* DARPA is a flat, nonhierarchical organization with empowered program managers.
- *Be entrepreneurial.* DARPA emphasizes engaging highly talented, entrepreneurial program managers, often with both academic and industry experience, who are willing to press their projects toward implementation. They serve for limited terms of three to five years, which sets the time frame for projects and ensures that new ideas are always coming into the agency.
- *Work with the researchers.* Program managers aren't just involved in the initial research award, but also work on an ongoing basis with their researchers to help them progress, linking them to resources, talent, and ideas.
- *Forego having DARPA laboratories.* Research is done entirely outside the agency; DARPA has no research laboratories of its own.
- *Focus on impact, not risk.* Projects are selected and evaluated based on their potential impact on achieving a demanding capability or challenge.
- *Seed and scale.* For promising concepts, DARPA provides initial short-term funding for seed efforts with the potential to scale to significant funding, but with a clear willingness to terminate nonperforming projects.
- *Ensure autonomy and freedom from bureaucratic impediments.* DARPA operates outside the civil-service hiring process and standard government contracting rules, which not only gives it unusual access to talent, but also speed and flexibility in contracting for R&D efforts.
- *Apply a hybrid approach.* DARPA often puts small, innovative firms and university researchers together on the same projects, thus giving firms access to breakthrough science and academic researchers pathways to implementation.
- *Build teams and networks.* At its best, DARPA creates and sustains tremendously talented teams of researchers around technology challenges; they are highly collaborative and networked to become great groups.

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- *Accept failure.* As detailed next, DARPA pursues high-risk projects for breakthrough opportunities and tolerates failure if the payoff from potential success is high.
- *Orient to revolutionary breakthroughs in a connected approach*. DARPA is focused not on incremental but breakthrough/radical innovation. It emphasizes high-risk investment, moves from fundamental technological advances to prototyping, and then, using connections to other organizations, attempts to hand off the production stage to the armed services or the commercial sector.

RISK FAILURE

DARPA's willingness to risk failure in pursuit of breakthroughs, as identified previously, is a particularly significant attribute. One researcher has argued that 85 percent of DARPA's projects fail to achieve the goals set at the outset.[48] The actual percentage may not be this high, but given that DARPA seeks revolutionary technology breakthroughs, the fact that initial goals don't always match what emerges should not be a surprise.

The agency has a record of canceling failing projects, but it also manages potential failure by curtailing and reorganizing other projects—sometimes based on new findings. Nonetheless, the record of technological accomplishments is breathtaking—and willingness to accept risk is a significant part of that achievement.

All of this speaks to DARPA's *outcomes* orientation; Richard Van Atta, who studied DARPA for the Institute for Defense Analysis, argues that this works because the agency does not impose strict metrics at the outset of projects, even though it does use progress milestones.[49] Instead, it actively manages projects and is directly involved on an ongoing basis with the research team, always aiming for significant results that can alter the status quo based on research developments. DARPA's active management approach complicates the issue of measuring DARPA success, but it can help shift at-risk projects to a success pathway.

Van Atta points, as an example, to DARPA's Assault Breaker project during the Cold War. It was unable to realize its initial goal of fully integrated, stand-off precision strike capability, but it did result in the technologies behind the JSTARS and ATACMS defense systems, which also delivered breakthrough precision capabilities.

USE THE ISLAND/BRIDGE APPROACH

Again, Bennis and Biederman argue that innovation requires locating the innovation group on an "island," protecting it from "the suits," the bureaucratic pressures in larger firms or agencies that too frequently repress and unglue the innovation process.[50] But they note that there must also be a bridge—the group must also be strongly connected

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to supportive top decision-makers who can press the innovation forward and provide the needed resources. The innovation strategist Avery Sen has argued that this is a foundational innovation model.[51]

Lockheed's Skunk Works[52], Xerox PARC,[53] and IBM's PC project[54] all exemplify the Island/Bridge approach within industry; the companies formed then shielded separate innovation teams from the business/bureaucratic side's interference. While the Skunk Works and IBM PC groups had strong bridges back to mainland decision-makers, PARC famously did not—and its story, told in chapter 5, shows the significant downside. DARPA has been able to rely on bridges to the secretary of defense and other senior DOD leaders to implement its advances.

From the beginning, then, Island/Bridge has been a key to DARPA's success; it is an examplar among federal R&D agencies in this respect.[55]

BUILD A THINKING COMMUNITY

A prerequisite for success with the Island/Bridge is building a community of thought leaders. In science, it is well understood that each contributor stands on the shoulders of others, building new concepts on the foundations of what came before. This applies to technology development as well. At DARPA, building a sizable "thinking community" has been key to success not only as a source of contributing ideas, but also because that community has played roles in both finding talent and building political support.[56]

Building a thinking community around a problem takes time to evolve, but it reaches a density and mass where ideas begin to accelerate. DARPA's thinking community—multiple generations of program managers and university research and industry teams supported by the agency—has endured to become a group of change agents and advocates as well.

LINK TECHNOLOGISTS TO USERS AND OPERATORS

Another key organizational feature of successful innovation organizations involves connecting the technology to those who use and operate it. This is critical to the introduction of technologies in the course of the back-end portion of the innovation process. DARPA's work on major defense technology advances such as drones exemplifies an effort to link technologists with operators, and thus to transform operations. Its work on personal computing and the internet, which shattered the arm's-length relationships in mainframe computing between technologists and operators/users, also exhibits the same drive to produce technologies that connect with operators. DARPA's Tactical Technologies Office is specifically designed to bring technologies into military tactical systems, attempting to use rapid prototyping to transition to air, ground, and naval operators.

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The DARPA model captures the key features of the extended pipeline model—strong initial research and linkages between researchers and the institutions that can lead an innovation through the later stages toward implementation—and goes even further to confront the additional issues presented by the challenges of innovation organization. These include overcoming the barriers to innovation presented by legacy sectors and the role in these sectors that can be played by change agents.

DARPA is a great example of the change agent role. It is an entrepreneurial innovator, but *within* DOD and the defense innovation system. To foster implementation, it usually must still rely on the military services and faces all the legacy pressures that they embody for the follow-on stages. A succession of secretaries and senior defense officials, also acting as change agents, worked to press these DARPA-driven technologies into implementation by the military services despite their initial resistance.[57]

Thus, DARPA stretches from the front end of the innovation system deep into implementation, itself acting as a change agent tied to other change agents at the decision-making level.

LESSONS FROM DARPA FOR ITS CLONES

DARPA is a multifaceted innovation organization organized around a strong innovation culture and traditions. Can it be copied?

There have been two successful attempts to clone DARPA in the US: and the Intelligence Advanced Research Projects Agency (IARPA), founded in 2006, and the Advanced Research Projects Agency–Energy (ARPA-E), founded in 2009.[58] ARPA-E undertook a careful evaluation of its positive technology contributions in a series of studies seven years after it was established,[59] and a detailed National Academies technical assessment has found that it has made significant progress toward fulfilling its mandate to foster breakthrough energy technologies.[60] ARPA-E research has led to the founding of more than 100 new companies and follow-on private-sector investments that more than doubled its federal R&D support. For its part, IARPA—which focuses not on commercialization but on working with its intelligence agency customers toward technology implementation—has had more than 70 percent of its projects that surpassed their development midpoints achieve at least one transition to an intelligence agency.[61]

Each of these two agencies is oriented toward meeting innovation needs in the energy and intelligence sectors, respectively—a significant difference from DARPA. Their early leadership, in both cases, came from technologists fluent with the DARPA model and its specific characteristics; they systematically adopted it and made the adaptations needed to fit with the nature of their sectors. For instance, as will be discussed in chapter 10,

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ARPA-E had to develop a technology transition capability because it lacked the access that DARPA enjoyed to a large military procurement budget and to technologies that venture capital (VC) firms were willing to back. IARPA had to find additional ways to connect with intelligence users and operators in order to implement the technologies that it was nurturing.

Like DARPA, both agencies were able to hire outstanding program managers, which is the critical creative level for a DARPA-like entity. But these agencies also benefited from having able leaders at the outset who understood that the initial culture and operational characteristics within any agency tend to lock in quickly and control its future. They saw that getting all that right was their central task so their new organizations could release creative energies in the way that DARPA has long been able to do.

There has also been a failed example of a clone. The Homeland Security Advanced Research Projects Agency (HSARPA) was authorized in the enabling statute for the US Department of Homeland Security in 2002 as part of the newly formed cabinet department's science and technology directorate. Although it initially hired a group of well-qualified former DARPA program managers, it was placed under a much larger budget and policy group that oversaw all its award decisions and contracts, sharply limiting its independence. The group with DARPA experience soon left in frustration. Dr. Tara O'Toole, the department's undersecretary for science and technology from 2009 to 2013, worked to rebuild HSARPA during the Barack Obama administration, but this effort was subsequently halted during Donald Trump's administration.

In March 2022, a new DARPA clone was established as an independent entity within the US Department of Health and Human Services (HHS): the Advanced Research Projects Agency for Health (ARPA-Health). It has enjoyed strong support from Joe Biden's administration, and in 2022, the program was authorized and funded at $1.5 billion.[62]

DARPA's success has compelled other countries to attempt implementing similar agencies. Japan has conducted two successive experiments with the DARPA model, Germany has attempted something similar, and Britain in 2022 initiated a new ARPA entity, the Advanced Research and Innovation Agency (ARIA), initially funded at £800 million.[63] Given such national and international interest in DARPA, what are some of the key lessons in standing up entities modeled in the US "advanced research projects agency" mold?[64] Five are particularly critical.

The first concerns *scaling up*. Who will do the scale-up for the technologies that an ARPA entity initiates? What will happen to prototypes once developed? What is the pathway beyond the agency itself?

The DARPA model goes well beyond doing neat science and technology projects; it is about getting them into *implementation, acceptance, and use*. If it can persuade DOD

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leaders of their value, DARPA can use the defense budget to scale up its technologies. DARPA also, particularly in the case of IT, has used commercial capital for technology scale-up. The US Department of Energy (DOE) has no acquisition budget, so ARPA-E initially hoped that VC would scale its energy technologies. But VC pulled out of energy technologies in 2008–2009 because they were believed to be too risky and long term to be viable investments. ARPA-E was required to get creative, as discussed in chapter 10, transitioning technologies to interested companies and encouraging follow-on applied research backing from other agencies. IARPA uses the intelligence agencies for its scale-up. ARPA-Health should have access to strong VC support for the biotech sector, where most of its proposed medical technologies will land.

Any new ARPA needs to develop a workable implementation pathway; otherwise, its technologies will go nowhere. If you don't know where your technologies are going, they will never get there. An ARPA housed in a mission agency, like DARPA, can count on the DOD to enable scale-up. Otherwise, ways in which private-sector capital must and will be involved need to be understood up front.

The second lesson concerns the "Island/Bridge" approach. If it is to nurture its technologies in an intense great group atmosphere, a new ARPA entity needs a protected island free of the bureaucratic influences that can stifle its creativity. This is a lesson from the problems that HSARPA encountered. Equally important, a new ARPA entity needs a bridge to decision-makers who can help implement its technologies and protect it from intrusion.

Third, *culture is critical*. The culture of a new organization tends to lock in during its initial months; it is very hard to change thereafter. So it is critical to obtain strong leadership, preferably with experience in the DARPA model, at the outset. A director must build an initial talent base that is strong; the DARPA model requires strong, empowered program managers who are ready to assume responsibility for nurturing new technology areas and capable of energizing such efforts. The director must not micromanage; team members need the freedom to fail.

Talented office directors are critical, too. At DARPA, they are typically experienced in the DOD scale-up process of implementing technology; each one manages an overall technology area, advises and support a group of program managers in that area, and helps hire talented program managers.

Fourth, *pursue breakthroughs*. DARPA has pursued what its veterans call "DARPA-hard" projects, which require breakthroughs, not incremental advances. A new ARPA must decide what challenges to pursue—it can't pursue everything, so it must select a manageable number of technology fields, depending on the size of its funding, and match the backgrounds of its program managers to fit them, preferably with a mix of industry

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and academic experience. Within the technology fields selected, its program managers, backed up by office directors and the director, need to select potential breakthroughs that can scale.

Finally, *political design is as important as the policy and operational design elements*. A new ARPA must be politically sustainable or it will disappear. DARPA and IARPA have historically enjoyed a certain amount of political protection thanks to their justification in the name of national security. ARPA-E, however, faced a contentious political world of differing energy priorities, as well as other competing energy agencies and labs that viewed its mission as a diversion of their own resources.

A new ARPA director has a critical task early on: spend time with legislative and executive branch leaders to explain the technology vision and progress being made. The new ARPA could also use a formal or informal advisory committee of respected figures connected to political as well as technology circles, who can also serve as advocates.

The political time horizon for any new ARPA is very short—far shorter than the time that technologists understand it takes for new technologies to move to implementation—which is typically a decade or more. Politicians are going to want to know why the new ARPA hasn't changed the world after, say, two years. Providing periodic, detailed assessment reports on progress, as well as data on follow-on private-sector support for supported technologies, can help manage this pressure. The reports should spell out the challenges being pursued as well—if these are powerful and the pathways to solutions are reasonable, the challenges will buy the new ARPA time. The "thinking community" that an ARPA can foster, as described previously, can also provide significant help. These communities can be hybrid, combining academic and private-sector researchers and experts in a support group, with the combination enhancing everyone's credibility.

The successes of ARPA-E and IARPA demonstrate the utility of creating a new R&D entity around a DARPA model. Translating an idea into a new form, though, is not simple, and there are many potential pitfalls. The lessons around scale-up, island/bridge organization, locking in an initial culture, pursuing breakthrough ("DARPA-hard") projects, and political design and policy design can help in this cloning process.

Of course, any new entity will have to adapt the model to suit the needs of its supporting agencies and the varying technology fields that it pursues. Already, the viability of the strong program manager–led approach to technology development, as exemplified by DARPA, is increasingly accepted as an alternative to the traditional peer-review committee approach. In a new ARPA, the two can be complementary: one more top-down and the other more bottom-up.

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7 BRINGING INNOVATION TO LEGACY SECTORS

The frontier was long seen as a force shaping American society.[1] Behind society's idea of the frontier was a common story: when American settlers faced frustration and felt that opportunities were limited, they could set out in covered wagons, head west, cross mountains if necessary, and open a new frontier.

While the American frontier officially closed in 1890, the US population was, until the 1980s, far more physically and socially mobile than that of other countries.[2]

"COVERED WAGON" TECHNOLOGIES

The American bent for technological advance shows a similar pattern, as Charles Weiss and I found in our book and articles on this "legacy sectors" subject, and drawn from here.[3] Typically, Americans find new technologies and turn them into innovations that open up new, unoccupied territories; we take "covered wagon" technologies to new technology frontiers and populate those frontiers. Information technology (IT) is an example. Before computing arrived, there was nothing comparable: there were no mainframes, desktops, or internet before this innovation wave. Americans launched IT into a relatively open technological frontier.

This has been an important capability for the US. Growth economics has made it clear that technological and related innovation is the dominant driver of growth, as discussed in chapter 1. The ability to land in new, open technological fields has enabled the US economy to lead the major Kondratieff waves (long-term economic growth cycles induced by technological innovations)[4] of worldwide innovation since the mid-twentieth century.[5] IT and biotech are recent chapters in this story.

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REVERSE THE WAGONS: LANDING IN OCCUPIED TERRITORY

While the US appears to have a capacity for standing up technologies in open fields to form complex new technology sectors, it has not been as good at taking covered wagons back east, so to speak—by which I mean going back over the proverbial mountains to bring innovation into the already occupied territory of established, complex technology sectors. This issue is not unique to the US, but the nation's reliance on innovation-driven growth makes it particularly problematic. This failure means that we leave most of our economy—the complex, established sectors that make up more than 80 percent of the US economy—outside our disruptive innovation system, with a corresponding loss of broader economic benefits. For instance, despite tremendous advances in technology, even Thomas Edison would be very comfortable with our current electrical grid.

Of course, the story is more complicated than the frontier thesis about American culture. Yes, it's difficult to reverse the covered wagons and go back east. There is also the fact that over time, established technology sectors develop characteristics that resist change. The underlying technologies in these established sectors themselves become cost efficient through standardization and the lock-in phenomenon sets in. Firms go through a kind of Darwinian evolution: the leading technology competitors survive, expand, and become adept at fending off new entrants; they build massive infrastructure resistant to competitive models; and they form alliances with government to obtain subsidies, typically through the tax system and supportive regulatory structures that tilt the playing field toward their model and away from challengers.

In other words, established, complex economic sectors, often themselves the result of earlier waves of innovation, combine into a technological-economic-political-social paradigm that is very difficult to unseat;[6] they plant a series of sophisticated minefields to protect their model and resist its disruption. This pattern applies to highly complex sectors of the economy where technologies are a factor, such as energy, healthcare delivery, transport, construction and physical infrastructure, education, manufacturing, and food and agriculture. Arguably, we can improve our growth rate and attack our employment and environmental problems by accelerating innovation in these neglected economic sectors.

A complex, established *legacy* technology sector can be defined as one that involves products and platforms that group complex technologies in the way that a gasoline-powered car includes an internal combustion engine, drive train, battery, computers, fueling systems, and tires. These complex sectors also have their own infrastructures and are supported by their established technologies, economic models, public policies, public expectations, patterns of technical expertise, and educated workforces. Combining these elements, these sectors become that technological-economic-political-social paradigm.

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The concept of the complex sector is a broad one. Ronald Rycroft and Donald Kash introduced the concept of complex technologies as those derived not from a single inventor, but rather from complex learning networks with connections outside a single firm to university researchers, collaborating firms, and suppliers.[7] They noted that complex technologies now dominate international trade in goods. But the idea of a complex sector is broader than this concept of complex technology and is closer to Christopher Freeman's idea of technology clusters that dominate innovation waves;[8] he found that technological systems encompass groups of innovations and the firms that support them, and they are linked both economically and technically.

Both Freeman and Carlotta Perez argued there was a "techno-economic" paradigm.[9] Here, we significantly broaden that concept to include political and social support systems. The idea of so complex a sector has features in common with the idea of "dominant design" introduced by James Utterback and William Abernathy and based on Raymond Vernon's product cycle theory.[10] A dominant design is one that becomes widely accepted in the marketplace and thus becomes the one to which innovators and competitors must adhere if they expect to develop significant market share. Once such a dominant design has set in, the emphasis shifts away from innovation in the overall system toward component innovation in technologies that can be launched on existing platforms. In turn, radical innovation is displaced by incremental innovation within the dominant design. This is how legacy sectors evolve.

Of course, the US is not the only nation to experience the economic and political barriers of established, complex legacy sectors. Japan's economy would be stronger, for example, if it could bring more IT-driven retail efficiencies to a nation of small shops or pursue large-scale agriculture rather than relying on small family farms. The frontier thesis aside, innovation in established, complex legacy sectors becomes even more complex once technological lock-in has occurred.

LESSON FROM CHINA

The remarkable, sustained, double-digit growth of the Chinese economy between 1984 and 2007,[11] and the continued strong growth until the COVID-19 outbreak in 2020, were due in part to the application of up-to-date technology to established sectors such as transportation, healthcare, construction, and energy. The Chinese strategy for becoming the leading developed economy is based on a model that calls for moving to and extending the technological frontier in these and other sectors, even as it applies well-known technology to huge projects that will modernize its infrastructure. It has organized its economy with large doses of government capital, labor, innovation, central controls, and

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stern political directives, relying on a rapidly expanding private sector that uses up-to-date technology to supplement a network of state-owned companies. China's model of pervasive technology advance throughout its economy—with government-backed capital support[12]—has a precedent (with differences, of course) in the economywide catch-up approach in postwar Japan and in South Korea and Taiwan in the 1970s and 1980s.

There is a lesson here for the US. If innovation is key to growth, and if a nation is bringing innovation into many sectors, both established and those at the technological frontier, then it may be able to boost its growth rate significantly. US growth might look different if the US could find ways to cut the Gordian knots that tie up the ability to innovate in established, complex technology sectors and bring innovation to those occupied territories.

Doing so might mean bringing innovation into our inefficient and expensive healthcare delivery system, along with new biotech-derived drugs. It could mean bringing online delivery, simulations, and game-based learning into education, or new materials, factory approaches, and IT into our transportation and construction infrastructures, or e-government into the widespread delivery of government services. There's a long list of possibilities. Perhaps we could even take our innovation covered wagon back east and bring innovation into our complex, deeply entrenched, and heavily subsidized energy sector.

BARRIERS TO INNOVATION IN LEGACY SECTORS

The American national innovation system has a dual structure, part suited to rapid innovation and part stubbornly resistant to disruptive change. The complex, established legacy sectors that resist change and erect barriers to disruptive innovation share common features that obstruct the market launch of innovations that are over and above the so-called valley of death between research and late-stage development discussed in earlier chapters, and apart from the other obstacles that have been the traditional focus of innovation policy.

Innovations in legacy sectors must penetrate a well-established and well-defended technological-economic-political-social paradigm in these sectors that favors existing technology. The paradigm is characterized by these barriers:

- *Subsidies* and *prices*, as well as *cost structures* that are what economists call "perverse," meaning that by creating a mismatch between the incentives of producers and broader social goals, they lead to unintended consequences and undesired results
- An *established infrastructure and institutional architecture* that imposes regulatory hurdles and other disadvantages to new entrants

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- *Market imperfections* beyond those faced by other innovations, including network economies, lumpiness (where firms and sectors experience disparate growth), economies of scale, split incentives, needs for collective action, and transaction costs
- *Politically powerful vested interests*, reinforced by public support, that defend the paradigm and resist innovations that threaten their business models
- A *financing system* for innovation organized around a timeline that fits IT and biotechnology but not capital-intensive legacy-sector innovations
- *Public habits and expectations* attuned to existing technologies
- An *established knowledge and human resources structure* oriented to the legacy sector's needs
- An *aversion to innovation* through limited research and development (R&D) and limited available alternatives ready for implementation

The market imperfections on the list deserve special mention. For example, some legacy sectors, such as small-scale agriculture, are so decentralized and fragmented that *collective action* is precluded. In others, *network economies* limit entry for new technologies that don't seem to fit those networks. Beyond these obstacles, more economically or socially desirable technologies that are driven by environmental or other nonmarket considerations must overcome the lack of agreed replacement standards against which possible alternatives can be judged.

FIVE MODELS OF INNOVATION

To contemplate stretching our scientific and technological capabilities to established legacy sectors of the economy, we need a working theory of innovation for these sectors.[13] Its design depends on a clear concept of how technological innovation takes place in the sectors in response to market forces, as well as how this process can be influenced by public policy. Unless we understand the ways that innovation typically enters the economy, we will not be able to extend innovation theory so it can apply to legacy sectors.

There are five models of this process, each the product of a particular period of technological history, as discussed next.

PIPELINE MODEL

The first model is the so-called pipeline or linear model, associated with Vannevar Bush[14] and explored in earlier chapters. In this model, basic research intended to push back the frontiers of knowledge can—if industry steps in—lead to applied research, which in turn leads to invention, prototyping, development, and finally innovation (i.e., widespread

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commercialization or deployment). While the literature has shown that this process wasn't really linear—technology influenced science and vice versa—"pipeline" is still the term generally associated with this approach.[15]

This model, as noted, was inspired by the World War II–era success of atomic energy, radar, and other technologies derived from advances in fundamental scientific knowledge;[16] it regained prominence in the 1990s from the example of the information revolution[17] (explored in detail in chapter 6) and from the promise of similar revolutions in biotech and nanotechnology. Over time, basic research in the pipeline model can lead to radical or breakthrough inventions that create new functionality, which makes it possible to do entirely new things unavailable through established technologies. This is a technology push model, with the government supporting R&D and hoping that the push results in advances—largely from industry—that eventually enter the marketplace. One idealized way to look at the pipeline model is that university researchers pursue technology ideas, push them onto the street from an upper window of their ivory tower in the form of a journal article, and hope that a capitalist will drive by in a stretch limo, pick them up from the street, translate them out of academic-speak, and do something constructive with them.

US basic research tends to take place at federally funded universities and research institutes, whereas product development happens in private industry.[18] As discussed in chapter 4, the bulk of federal nondefense R&D agencies in the US—the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Office of Science at the US Department of Energy (DOE), to cite the three most prominent examples—follow Bush's design and invest in basic research.[19]

Compared to the situation in many other countries, the US system works well at this early stage: competitively awarded basic research, funded predominantly by government, can lead to dramatic follow-on technological advances.[20] Even so, as discussed in earlier chapters, this institutional separation gives rise to a difficult-to-finance gap between the proof of concept in a university laboratory and development of a commercializable product that is attractive to venture capitalists and industry. This gap, between research and later-stage development—the valley of death explored in chapter 4—is where most new technologies die, whether they were intended for legacy or nonlegacy sectors.[21] The emphasis on radical innovations embodying the potential of new functionality, however, is well suited to an American temperament oriented toward opening new frontiers—to bringing on the "next big thing."

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INDUCED INNOVATION MODEL

The second of these models is the so-called induced innovation concept explored in detail by Vernon Ruttan,[22] in which technology and technological innovation respond to the economic environment.

Federally funded research leading to radical or breakthrough technologies is not the only driver of innovation. Industry, of course, plays a profoundly important role. Ruttan observed that innovators spot established or niche markets susceptible to the entry of new technology and then move to fill them. This kind of innovation typically takes advantage of incremental or secondary technological advances, as opposed to radical ones, and is led by industry.

The induced innovation concept holds that the technology being used in any economic sector—and, given enough time, the direction of R&D—responds to changes in the market, such as price signals, by minimizing the use of expensive inputs and maximizing the use of inexpensive ones. By extension, this model would predict that technology and technological innovation would also respond to the policy environment—for example, by improving worker and product safety and decreasing pollution as policies in these areas are tightened.

The induced innovation model was one of several models that emerged in response to the realization that nations that were superior in basic research, such as Great Britain in the 1950s and 1960s, were not necessarily leading innovators, and that a majority of new products used existing technologies to meet new market needs—incremental advances—rather than emerging from basic research. The model involves "technology pull" and is sometimes referred to as "market pull" or "demand pull": the market inspires and encourages technology innovations from firms for implementation in the market.

The induced innovation model assumes that a technology can enter the marketplace more or less automatically once the appropriate market incentives are well established. This is not always the case, however, especially when the technology in question faces competition from established legacy technologies, such as those dependent on fossil fuels. Obstacles to innovations that are derived from the results of long-term research may appear at the classic valley of death between research/proof of concept and development/first product. But others may appear at a later stage, when the product is ready for market launch at scale, a time that is especially critical for innovation in legacy sectors. In particular, induced innovation in legacy sectors is typically hampered or blocked by price structures, market imperfections, and other obstacles that favor and help entrench incumbent technologies.

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EXTENDED PIPELINE MODEL

Neither pipeline nor induced theories of the dynamic of innovation fully encompass the role of government in innovation.[23] Government policies can limit innovation, particularly when they form part of a disruption-resistant technological-economic-political-social paradigm protecting a legacy sector through regulatory intervention. In many cases, however, the opposite takes place: government can serve not only as technological initiator and change agent at the research stage, as captured in the pipeline model, but also in the follow-on stages. In this case, the business sector, which is inherently more risk averse and short term in its outlook, invests only after entrepreneurial governments have made the high-risk, longer-term investments.

The potentially positive role of government in research, development, prototyping, demonstration, test beds, and often initial market creation is understood by at least some experts as a result of the success of the IT sector,[24] as explored in chapter 6. As noted, microprocessor advances, personal computing, supercomputing, the internet and the web, cloud computing, broadband and mobile communications, and robotics—economic sectors now producing hundreds of billions of dollars in revenue annually—all had origins in federal support.[25] For example, nearly every technology that makes Apple's iPhone so smart was funded by the US government: the global positioning system (GPS), the internet, the touch-screen display, and the voice-activated command system of Siri.[26] The US Department of Defense (DOD) has played a particularly critical role in the advance of IT.[27] Biotechnological and pharmaceutical advances are also beneficiaries of this government role.[28]

We call this model, whereby government participates not only in R&D, but also in the later stages of the innovation process through the customer's role in market creation, the *extended pipeline*. The extended pipeline theory is not new in itself; rather, it is a variation on and an extension of the pipeline theory ascribed to Vannevar Bush, intended to overcome the front-end-only limitations that he imposed on it and to capture the reality of a deeper governmental role than was previously understood. Like the pipeline, it is a "technology push" model. Government's role here is not simply the more modest one of intervening in cases of market failure, as envisioned in classical and neoclassical economics, but also one of shaping and creating markets.[29] It has operated across the full spectrum of innovation advancement, and has enabled private-sector entry that takes place only after government has assumed the initial risk.

This governmental role, though, is not well understood by either the public or by politicians, a fact that has operated as a brake on both recognizing future opportunities for innovation and reaping of the full rewards of contemporary innovation-driven capitalism. This extended pipeline system has operated predominantly through the DOD,

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which led most of the Kondratieff innovation waves of the twentieth century—from aviation to electronics, nuclear power, space, computing, and the internet—and which tends to operate at the innovation frontier rather than in legacy sectors. The government's role in medicine, industrial agriculture, and aerospace provides other examples of this kind of active involvement. Changing attitudes to this model are discussed in chapter 12.

MANUFACTURING-LED MODEL

The fourth model of the dynamic of innovation, another "technology push" model that is not discussed in the innovation literature, can be referred to as the *manufacturing-led* model.

Innovation in the US is generally associated with the front end of innovation, which encompasses the stages of R&D through prototyping; manufacturing is not typically understood as part of the innovation process.[30] This is an inherently disconnected view; innovation must be looked at as a system that stretches from early-stage research through to production and market introduction. The US view contrasts with the perspectives of Germany and Japan, cultures that emphasize engineering, artisanship, and quality, and that have histories of innovation and success in production.[31] Both see production as being at the core of innovation and have run major trade surpluses in manufactured goods, unlike the major deficits in the US.[32]

Innovative approaches can be pervasive at the production stage and take years to bear fruit. Deep challenges must be resolved: designing a product that will optimally suit a potential market; carrying out engineering design; overcoming problems of production and component cost; determining and forming production processes; creating efficient production systems; developing and applying new production and product business models; educating the production workforce in the new system; building a supply chain; financing production scale-up; scaling up production to fit evolving market conditions; and reducing all these steps to a routine.

These are also highly creative processes. They are enabled by ensuring that manufacturing requirements are fully integrated, preferably when a product is first being designed, but at least by the time of the beginning of production at scale. In either case, this entails extensive engineering and science. Often, the initial concept of the innovation itself and the science behind it must be completely rethought and reworked to fit production, cost, and market needs. In addition, many firms find that because there is so much "learning by building," the first production plant must often be written off, as the second plant can be made much more efficient by applying lessons drawn from the initial production experience.

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Front-end R&D begins the innovation process, but the subsequent stages through initial production at scale are just as critical, not only for incremental technology advance but also for radical or breakthrough innovation. In sum, much innovation is "manufacturing led"; this must be regarded as a key approach to innovation and a model in its own right. It is a critical aspect of "technology-push," but it also serves the incremental and secondary advances of induced, "demand pull" innovation.

The US excelled at manufacturing in the past, developing interchangeable machine-made parts (as discussed in chapter 4) and, in the second half of the nineteenth century, inventing a paradigm around mass production to serve a continent-sized economy.[33] But following the creation of a powerful front-end innovation system in the post–World War II period, US innovation has tended to become front-end loaded, emphasizing R&D as opposed to its previous focus on production. Since today's innovation system must also embrace the back end—the prototype, demonstration, test-bed, and initial production phases—the US has a problem, as discussed in subsequent chapters of this book. China, which now exceeds the US in manufacturing net output, emphasizes the back end of innovation, particularly production, even as it works to build its front-end R&D system. Although many have assumed that China has achieved its production leadership through lower wages and costs, studies suggest that it is able to scale up production volume rapidly through advanced processes that are integrated across regional firms and tied to system efficiencies and cost savings.[34]

Just as there are limits to front-end innovation, there are limits to manufacturing-led innovation. Some Asian economies, including Taiwan and South Korea, have emphasized this manufacturing-led stage, but they have begun competing with lower-cost economies in areas that were increasingly dominated by commodity goods and faced slower growth. In other words, they grasped the back end but now are also emphasizing stronger front-end innovation in areas such as semiconductors. The US has been working the opposite course.

The lesson seems to be that strength on both front- and back-end innovation appears to be complementary. While the US retains a strong front-end innovation system, it has not understood the need to extend its view of its innovation system to include production. It has failed to grasp the importance of manufacturing-led innovation, although this remains an important innovation model.

INNOVATION ORGANIZATION MODEL

Innovation requires not only technology supply and a corresponding market demand for that technology, but also organizational elements that are properly aligned to link the two. This leads us to a fifth model for the dynamic of innovation: the concept that

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innovation organization is required to form a new technology and to link—and, if necessary, orchestrate—the disparate institutions and firms needed to launch it, overcoming any institutional or policy obstacles that come up along the way. This innovation must be anchored in both the public and private sectors because these sectors are otherwise inherently disconnected.

This *innovation organization* model combines the first four innovation models, but it moves beyond them to overcome or circumvent the obstacles in the innovation environment and identify and facilitate the work of the change agents that confront them. This function is particularly important in legacy sectors, in which these obstacles are particularly problematic. It is implicit in the other four models, but it deserves to be explicit in its own right. While each is critical, innovation organization is the "one ring that rules them all." This fifth model, however, can be glimpsed only sporadically in the innovation literature.[35]

To facilitate the evolution of new technologies in response to the forces of technology push and market pull, there must be concrete institutions for innovation and organizational mechanisms connecting these institutions. The US needs this fifth model in our innovation framework: the idea that innovation requires organizations anchored in both the public and private sectors, to form and launch the new technology, if innovation theory is to be practical, creating ideas we can actually implement.

These five theories fit into a historical context. The induced technology model is partly a product of the historical perspective of the 1960s through the 1980s, with advances derived largely from incremental gains in existing technology. Throughout that era, of course, the kind of innovation described by the pipeline model was humming along, bringing about an IT revolution in the 1990s after decades of government R&D inputs. This was accelerated and enabled by the extended pipeline approach led by DOD.

While the induced model best fits incremental innovation, the pipeline and extended pipeline models best fit breakthrough or radical innovation. In turn, realizing technological advances, incremental or breakthrough, required manufacturing-led innovation. Underlying all these developments were organizational issues, vital for our innovation system and yet largely unexplored. This fifth model of the dynamics of innovation stretches beyond the other four models to reach not only technology supply and market demand, but also the entire innovation system, from the front end through to implementation. This model encompasses the others.

In decentralized sectors where there are many private firms, as exemplified by manufacturing in particular (but also by many high-tech fields), there must be a chain of institutions—from research through to implementing firms, with links connecting them—to enable new technologies to evolve to meet radically new requirements or to

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translate radically new capabilities into practical applications. That is how technology push is enabled to meet up with and satisfy market pull.

Legacy sectors are complex and often massive—consider energy and healthcare delivery, for example. Bringing innovation into a legacy sector requires the application of *all* the innovation dynamics embodied in these models. To tackle the energy challenge will require not only R&D through the pipeline model, but also the reach of the extended pipeline, the application of the manufacturing-led model, innovation from firms through the induced innovation model and, overall, an effective innovation organization framework.

INTEGRATING THE FIVE MODELS

The induced, pipeline, and extended pipeline models have been viewed as separate and distinct paths—one led by industry, the others largely by government. We must combine and integrate these induced and pipeline innovation models if we are to describe adequately the innovation framework required for innovation in energy and other complex legacy technology areas.

The induced technology literature has rested primarily on market pull and the role of firms in filling technology needs based on changing market signals. It does not deal directly with the role of government. The pipeline and extended pipeline depend on a longer-term government role. The manufacturing-led model, as discussed in chapter 9, will increasingly rely on industry-government collaboration for the introduction of new technologies and processes. A focus on the organization for innovation offers the opportunity to bring these separate strands together. Although the literature is quite limited, the organization of innovation at the institutional level reflects on connections among firms, the academy, and government entities such as the Defense Advanced Research Projects Agency (DARPA).

Firms, universities, and government organizations will all be major players in, for example, new energy technology. Yet the dominant literature on technological innovation in recent years has remained focused on the strengths and weaknesses of the pipeline model because of the importance of the IT and the biotech innovation waves for which this model provides a partial description. This pipeline-oriented literature pays too little attention to how the overall economic and policy environment affects technological innovation in complex networks of both related and unrelated technologies, and the induced model often pays too little attention to the governmental role. To date, neither has focused much on the overall direction, innovation organization. And there isn't a body of literature on the extended pipeline and manufacturing-led dynamics of innovation introduced here.

Innovation policy must confront the problems involved in complex technology sectors. These sectors require a very different analysis from the three separate strands that

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have been the focus so far of the US literature on technological innovation. While each of these three models helpfully describes aspects of the innovation process relevant to bringing change to legacy sectors, research on the other two is absent. And it turns out that only by integrating all five in a unified approach can we move toward a better grasp of the task before us: innovation in a complex, established legacy sector. Indeed, in taking on this task, we will be able to draw a new series of policy prescriptions that are quite different from the approaches that have been articulated thus far in other sectors.

THE CHANGE AGENT

Whatever the model, innovation doesn't just happen. Even if the elements for an innovation system are assembled, someone or something must serve as the catalyst for change. That person or organization is the *change agent*. Like innovation itself, change agents must operate at both the institutional and the personal, face-to-face level. And, as usual in human affairs, there is no substitute for leadership.

The change agent, whether an institution or an individual allied with an institution, must be a policy orchestrator, pulling threads of policy options together to effect change and drive the innovation. The agent, therefore, must have available at least potential technological innovations, the positioning needed to push them, and the ability to identify, access, combine, and deploy the innovations *and* the complementary policy instruments needed to exploit them.

The change agent takes a different form depending on which model the innovation process follows. In the pipeline model, where there is a major institutional gap between basic research organizations that pursue discovery and industry's pursuit of the later stages of implementation, the key job of the change agent is to find a bridge across this gap from among the few that may be available.[36]

In this case, the change agent is likely to be industry, particularly a small firm or entrepreneur that is prepared to pursue a radical innovation from research to a commercial product, sometimes with the aid of a technology transfer office in a university or government laboratory. As an example, many early software advances were supported by federal research. The critical computer language for what became desktop computing was BASIC, developed by Dartmouth researchers from an NSF grant. It was both simpler to program with and able to reach sophisticated levels. It took Bill Gates, Paul Allen, and their Microsoft "Microkids" team to apply BASIC to early microcomputers, from the earliest Altair through the IBM personal computer (PC), making Microsoft's application of BASIC effectively the industry standard for initial generations of PCs.[37]

The induced innovation model is inherently less ambitious (because it is typically incremental) and more connected. Here, the change agent also comes from industry.

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A firm sees a market opportunity, typically for an incremental or secondary technological advance, and moves to meet it. This is the story, for example, of Boeing's 787 Dreamliner. While jet aircraft were initially nurtured and sustained for decades by the military, military and civilian aircraft designs eventually diverged. The 787 applied a series of incremental advances to reduce weight, improve performance, and cut fuel consumption—filling a market need of the commercial airlines.

The manufacturing-led innovation model is exemplified by Japan's adoption of its famous quality manufacturing paradigm in the 1970s and 1980s, described earlier in chapter 4, with Japan's industrial leadership serving as the change agent. It was based on ideas by W. Edwards Deming, who developed the ideas behind what came to be known as Total Quality Management. Deming's principles were implemented most famously in the Toyota Production System, which led to a production renaissance in Japan, allowing the nation to capture leadership in the auto and consumer electronics sectors.[38]

The extended pipeline, as discussed earlier, is an attempt by federal R&D agencies (largely in the defense sector) to reach further down the innovation pipeline past basic research toward implementation. Here, the change agent can be an agency, best exemplified by DARPA, in which empowered program managers press to get their technology implemented and, in this way act as change agents.[39] Typically, the agency employs the "island-bridge" approach described in earlier chapters, developing the innovation in protected isolation (the "island") from bureaucratic pressures, but uses a "bridge" to a senior DOD decision-maker to press the advance. This is the story of DARPA developing stealth, unmanned aerial vehicles, and precision strike innovations with backing from senior DOD leaders.[40]

Pursuing only one or two of the models for innovation is not enough when attempting to bring innovation into complex legacy sectors. *All five models* will need to come to bear in the form of the overall innovation organization model. Change agents will be needed throughout. Operation Warp Speed (OWS), which developed and distributed new vaccines for the coronavirus pandemic (discussed in chapters 8 and 12), exemplifies this integrated approach. There a new government entity operating across agencies and, in collaboration with industry, served as the orchestrator and change agent.

INNOVATION IN LEGACY SECTORS: A FOUR-STEP ANALYTIC FRAMEWORK

We have explored the five dynamics by which innovations can be developed—embodied in the five models just discussed—including the need for a unified approach in the form of an integrated model. But how do we actually introduce innovative new technologies into legacy sectors?

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The most difficult step in developing and deploying new technology in established legacy sectors is launching technologies into extremely complex and competitive markets. A focus on the point of market launch means that any program of government support for innovations in these technologies should be organized around the most likely bottlenecks to their introduction to the market.[41] This perspective goes beyond the long-standing focus of pipeline theorists on the valley-of-death stage between research and late-stage development.[42]

Let's begin with the principle that public policies to encourage technological innovation should enable alternative technologies to compete on their merits; that is, these policies should be as technology-neutral as possible. This leads to the need for an integrated consideration of the entire innovation process, including R&D and deployment or implementation, in the design of any program to stimulate innovation in energy or any other complex, established technology. This requires drawing on the pipeline, extended pipeline, induced, and manufacturing-led innovation models and integrating them through the innovation organization model. Deep systems issues of organization for innovation must be considered because new organizational routines will be needed across both the public and private sectors to facilitate integrated policies to support innovation.

These considerations lead to a new framework for innovation policy. Getting to that framework, and thus to the policy, requires a four-step analysis, proposed here as the basis for innovation policy in this area of legacy sectors.

STEP 1: IDENTIFY THE TECHNOLOGY LAUNCH PATH

The first step of this analysis requires assessing the range of promising technologies that could enter a legacy sector, based on the likely bottlenecks in their launch path, and classifying them into groups that share the same likely bottlenecks. Evolving technologies for the energy sector and a number of other legacy sectors fall into four technology launch pathway categories. Relevant policies for each can be designed to support their launch.

First, there are *experimental technologies* that require extensive long-range research. The deployment of these technologies is sufficiently far off that the details of their launch pathways can be left to the future.

Then there are the *disruptive technologies*, potentially disruptive technological innovations that can be launched in niche markets.[43] These may expand from this base as they become more price competitive.

Finally, there are *secondary technologies* with two pathways. The *uncontested launch* group of secondary technologies includes secondary component innovations that will

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face market competition the moment they are launched but will likely be acceptable to recipient industries if their price range is acceptable. These technologies must face the rigors of the tilted playing field, such as a competing subsidy, or the obstacle of a major cost differential, without the advantage of an initial niche market. The *contested launch* group of secondary technologies are secondary component innovations that have inherent cost disadvantages and/or that can be expected to face economic, political, or other nonmarket opposition from recipient industries or environmental groups. They must overcome these obstacles in addition to those facing the technologies in the *disruptive* and *uncontested launch* categories.

The existence of secondary technologies complicates the technology launch picture because components do not land in open frontiers, but instead land in existing systems or platforms—that is, in occupied territory. While the potential for disruptive technologies that can open new innovation frontiers will increase, that opportunity will take time to evolve.

One other category that must be accounted for—*improvements in manufacturing technologies and processes*—is a crossover because it includes the previous categories for new technology as well as existing technologies. These are improvements for which investment may be limited because cautious investors are reluctant to accept the risk of increasing production capacity and driving down manufacturing costs until they see an assured market. Driving down costs and improving efficiency will require advances in both manufacturing processes and technologies appropriate to the particular new technology categories summarized here; support will also be required to scale up manufacturing so that efficient new products can move into the market more quickly.

STEP 2: DEVELOP SUPPORT POLICIES TO PROMOTE THE INNOVATION

The second step of the analysis is to classify support policies for encouraging energy innovation into technology-neutral packages, and then match them to the technology groupings developed in the first step of the analysis. This assumes that there will be a governmental policy interest and, therefore, potential government support to bring new technology into the legacy sector. This will be present for many, if not all, innovations in legacy sectors such as energy, healthcare delivery, transport, education, manufacturing, and construction, where government already plays a significant role.

Three policy elements stand out here. First, there is the need for *front-end technology nurturing*. For technologies in all the step 1 experimental, disruptive, and secondary technology categories, technology support is needed at the front end of innovation before a technology is close to being commercialized. This includes direct government

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support for R&D in both the long and short terms, as well as for technology prototyping and demonstrations.

Second, *back-end incentives* may be needed to encourage technology transition as a technology closes in on commercialization. Such incentives can encourage secondary/component technologies facing both uncontested and contested launch, along with incremental innovations in technology for conservation and end use and technologies for manufacturing processes and scale-up. They may also be relevant to some disruptive technologies as they transition from niche areas to more general applicability. These incentives include tax credits of various kinds for new technology products, loan guarantees, low-cost financing, price guarantees, government procurement programs, buy-down programs for new products, and general and technology-specific intellectual property policies.

In the field of energy technology, procurement by the DOD, the nation's largest owner of buildings and facilities, provides an example. DOD could offer its facilities as an energy-efficiency test bed as an incentive to help ascertain the optimal approaches to building technology. For the department itself, this offers potential energy cost savings over time. There are challenges, however, such as avoiding abuses that could arise when deviating from lowest-cost procurement criteria. How could such procurement be reconciled with the technology-neutral strategy advocated here? Despite the potential complications, though, this may be one of the better levers for lifting infrastructure out of the current technology steady-state.

The third policy element is *back-end regulatory and related mandates*. If incentives are the carrots, these are the sticks that may be needed to encourage component technologies facing contested launch, and also some conservation and end-use technologies. Such mandates include efficiency standards, taxes (such as a carbon tax to cut energy emissions), regulations, and so on.

Just as there is no one-size-fits-all R&D program, R&D efforts need to be tailored to particular technology categories. Hence, particular carrot-and-stick approaches may fit one group of technologies but not another. Loan guarantees may work for larger firms, but they likely will not be useful to small firms and start-ups with limited capital access for deploying new technologies. Analytical work is also needed to evaluate the relative economic efficiency of particular back-end incentives or regulations.

As suggested in the previous section, the optimal approach to bringing innovation into complex, established legacy sectors would be to bring to bear *all five* models of the innovation process through an integrated model. A technology supply approach (such as in the pipeline and extended pipeline models) is unlikely to be effective unless it is

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accompanied by the demand-side price signals called for by the induced innovation model. Even when they are technically ready, new entrants often cannot compete in a legacy sector on price with existing mature, efficient, and cheap technologies—at least initially. It takes time for a new technology to drive down the price curve. So incentive carrots and regulatory sticks may be required.

Induced innovation depends on a robust technology supply program, supported by a strong pipeline innovation system, to enable the technologies that are needed to create alternatives and drive down costs to become available within a reasonable time. This is particularly true when the technology transformation being sought is significant. Innovation in a complex sector is never either/or when it comes to the optimal model, which is why the integrated model is necessary.

STEP 3: IDENTIFY THE GAPS IN THE INNOVATION SYSTEM

The third step of our analysis is an institutional gap analysis: to survey existing institutional and organizational mechanisms for the support of innovation to determine what kinds of innovations (as classified by the likely bottlenecks in their launch paths) do not receive federal government support at critical stages of the innovation process, as well as what kind of support mechanisms are needed to fill these gaps.

In many legacy sectors, for example, we lack the capacity to translate research into innovation, finance the scale-up of promising technologies, and form an overall collaborative strategy between the public and private sectors to map the details involved in developing and deploying the new technologies at scale. These are innovation system gaps and must be identified.

STEP 4: FILL THE INNOVATION SYSTEM GAPS

The fourth step in our analysis is to recommend new institutions and organizational mechanisms to fill the technology gaps identified in step 3, such as by providing translational research, technology financing, and road-mapping.

The four steps described here for technology implementation reinforce the need for an integrated approach. The steps embrace the five models, employing aspects of each. The first of these four steps draws on the pipeline model, suggesting that support from the government pipeline will be important to creating, launching, and enhancing a range of technology options. The extended pipeline model is relevant in in this step as well. But since the technology streams generally will need to land in the private sector at a large scale, the second step relies on the induced innovation model, where industry plays the key role. It concentrates on the policy—the demand signals—that will induce the private sector to take up, modify, and implement the technology advances that can

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originate from the innovation pipeline models. Whether these come from a demand pricing system like the cap-and-trade scheme proposed for carbon-based energy, from technology incentives, or from regulatory requirements, they will need to be coordinated and, to the extent possible, will need to be technology-neutral. The manufacturing-led model can also play a role at this implementation phase. The third and fourth steps draw on the integrated approach of the innovation organization model advanced here: that the gaps in the innovation system will need to be filled for the handoff to occur between pipeline and induced models, especially at the points where technology supply push meets market demand pull.

APPLYING INTEGRATED INNOVATION ANALYSIS TO COMPLEX SECTORS

The US economy would be well served if it developed a capacity to move technological innovation more efficiently into established, complex economic sectors. Our traditional model for innovation relies on launching innovation into open fields; we could improve our innovation-based growth rate if we learned how to drive our technology-laden covered wagons into old frontiers, not just new ones. This requires a new innovation framework that integrates all five models for innovation articulated in this chapter—pipeline, extended pipeline, induced, manufacturing-led models, and innovation organization. This framework requires a new focus on the moment of technology launch, as well as innovation policy's traditional focus on the valley of death. A four-step approach for introducing new technologies, from support for the front-end stages of R&D, testing, and prototyping, to policies (both carrots and sticks) to induce the private sector to run with these technology advances, to identification of and filling innovation system gaps, is in order.

But even if we equip ourselves with a new model for innovation policy in complex, established, legacy sectors such energy or healthcare delivery—policies for taking our technology covered wagons east—we should not underestimate the difficulty of the process for introducing new technology at the massive scale demanded. It is a process that has eluded us for decades in many legacy sectors.

These complexities underscore the need for a comprehensive new theoretical approach, such as the one proposed here, that takes us well beyond the relatively straightforward issues around bridging the valley of death that has long been the focus of innovation policy. Confronting legacy sectors will force a new policy agenda.

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8 EXAMINING LIFE SCIENCES INNOVATION

Science and technology policy is not uniform across different fields and sectors; it varies by context. The general policies that we have discussed so far, therefore, must be applied to particular fields. This chapter and the upcoming ones embark on a series of case studies of individual technology and economic areas, beginning with policy for innovation in the life sciences sector.

THE NATIONAL INSTITUTES OF HEALTH

The National Institutes of Health (NIH) is central to the story of life sciences policy in the US. The NIH has a long bureaucratic lineage.[1] It originated in 1887 as a bacteria lab in the attic of a Staten Island, New York, hospital as part of a federal program that served ill and diseased merchant seamen. The lab moved to Washington, DC, in 1891 and then merged into to the newly created Public Health Service in 1912. In 1930, the lab was redesignated as the National Institute of Health and, in 1938, moved to its current sprawling campus in Bethesda, Maryland. In 1948, as new institutes and centers were formed, it was renamed the National Institutes of Health (NIH).

Vannevar Bush had proposed "one tent" for federal research under what later became the National Science Foundation (NSF), but President Harry Truman vetoed his plan (see chapter 3); the NSF was not formed until 1950. Science, meanwhile, did not stand still, and existing research agencies such as the NIH began to grow. Between 1945 and 1950, the NIH budget multiplied from $2.8 million to $52.7 million and has been expanding ever since. While government funding for research in other disciplines has been increasing at a rate similar to inflation since the 1970s, research funding for NIH nearly tripled through the 1990s and early 2000s. By 1992, NIH constituted nearly 1 percent

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of the federal government's total operating budget and controlled more than half of all funding for health research, supporting 85 percent of all funding for health research in universities.[2]

Although funding for NIH stagnated for a period after Congress had doubled its funding between 1998 and 2003, it has been growing again in recent years; its 2022 budget was $45 billion. It has become the world's behemoth of medical research, with both intramural research on its campus in Maryland and extramural research supporting university health science research nationwide.

While Bush's proposal for a single tent for science failed to come to fruition, his basic research concept prevailed, and NIH is squarely on the basic research pathway. It is divided into twenty-seven separate institutes and centers because for decades, Congress—whenever an organization of patients and families afflicted by a particular disease grew powerful enough to lobby—would appease the disease group by legislating a new dedicated institute to pursue its disease. Each disease became a separate cause, with separate supporters, and the budgets for NIH's individual institutes tend to reflect the prevalence of each disease and the political heft of its constituents.

It has few connections to other research agencies, is overwhelmingly oriented to biology, and has limited ties to industry. What Anthony Fauci, the noted head of NIH's National Institute of Allergy and Infectious Diseases (NIAID) from 1984 to 2022, once declared about his institute is generally true of all the others: "The path to product development has not been part of [NIAID's] research strategy."[3]

THE NATIONAL INSTITUTES OF HEALTH AND THE BIOTECH MODEL

NIH has had a profound impact on life sciences research and has made many critical contributions. Fauci's remark notwithstanding, NIH-supported research has found a way to link to an emerging biotech model that has already enabled an explosion of new medical advances. How did this evolve?

First, *NIH has trained a massive health innovation army*. As the economist Paul Romer argued (as discussed in chapter 1), progress in a field requires building a "research mass." A significant group of well-trained prospectors must be formed to build up the knowledge base in a field so it can be expanded and scaled up into working technologies. NIH's research portfolio, which dwarfs that of other American research agencies, has enabled this major and growing talent base in the life sciences. For instance, life sciences graduate students in US universities are educated primarily through mentor-based research projects. When the dominant funder is NIH, they learn by doing under faculty principal investigators on research projects.

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Further, *the NIH-supported talent base spawned the biotech sector*. Even though not well connected to industry, it is that "army"—the NIH talent base—that became a massive and growing knowledge base and in turn enabled the emergence of the biotech sector in the 1980s. The biotechs were founded by researchers educated at universities and making discoveries funded by NIH research awards. The biotechs, in turn, provided a mechanism to move research advances into medical products.

The examples are numerous. Genentech, the first biotech company, was founded by Herbert Boyer, an NIH-funded researcher working on recombinant deoxyribonucleic acid (DNA) at the University of California at San Francisco (UCSF). As recounted in chapter 5, he teamed up with Robert Swanson, who had chemistry and business degrees from the Massachusetts Institute of Technology (MIT) and brief experience in the early venture capital (VC) industry, at a famous 1976 meeting at Churchill's Bar in San Francisco.

Biogen, the second biotech company, began after Phillip Sharp—an NIH-funded MIT professor and later a Nobel Prize winner for his work on ribonucleic acid (RNA)—advised a company to take a major stake in Genentech after meeting with its scientific team in 1977.[4] He saw the biotech model, returned to MIT, and persuaded Wally Gilbert, a noted NIH-funded Harvard professor and also a subsequent Nobel Prize winner, to join him. They signed on a dream team of leading life sciences researchers and formed Biogen in 1978, which, like Genentech, remains a major biotech firm.

The model that these firms exemplified led to a plethora of venture-funded biotech firms and major innovation hubs in Boston and San Francisco, fueled in part by the fact that *biotechs can get long-term capital for a decade or more before their products enter the market*. This stands in sharp contrast to most other sectors. For instance, entrepreneurial physical science–based companies trying to bring new hard tech products to market that have to be manufactured typically can get VC funding for a total of five to perhaps seven years for technologies no more than two to three years from production. It's a different timeline for drug discoveries; VC funding can continue for ten to fifteen years before market introduction.

How did this evolve? One key to this is the value of intellectual property: patents protecting intellectual property enable recovery of monopoly rents for the twenty years of the patent term. But there are other critical elements. The US Food and Drug Administration (FDA) has a well-established process for drug approval, and no drug can enter the market that does not successfully pass through it. The three successive stages of FDA's clinical trials (animal testing, small-scale human testing, and large-scale human testing) allow venture capitalists to gauge their support because the chances of a technology making it through each stage are well understood, as is the potential size of a drug's market. It typically takes seven years and well over $1 billion in clinical trials to obtain FDA

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approval, and the FDA process enables risk staging, which enables investment benchmarking. Knowing these risk levels, investors can build a risk portfolio for investment at each phase.

Biotech firms have a love-hate relationship with the FDA. Biotechs hate the agency because it represents a major barrier and time sink that they must endure before they can get a technology to market, but they also love it because its approval of drugs and medical technologies carries so much power that once obtained, this approval virtually guarantees the drug a market overnight.

The FDA is the most respected drug and medical technology review agency in the world, and its approval amounts to a technology validation. No other technology sector, and certainly not hard tech, has such a technology validation system, which makes market entry in nonmedical fields often quite chaotic and much more subject to random chance.

Another strength here is that *the biotech model has eliminated science's "upstairs/downstairs" of academia and the commercial world.* Academic scientists long maintained a certain disdain for the commercial sector, an attitude inherited from the Germans, after whose universities American universities were modeled. The academy did the discovery and companies did the applied work, and the latter was not typically held in the highest esteem.

After founding Genentech, for instance, Boyer faced ostracization from some of his UCSF colleagues for "going commercial," but he remained determined to translate his research into remedies. When Genentech created the first synthesis of insulin in 1978, the criticism quieted. Similarly, when biology all-stars like Sharp and Gilbert founded Biogen in Kendall Square in Cambridge, Massachusetts, near MIT, resistance to forming biotechs faded.

MIT's famed Robert Langer recalls the reaction when he started his first biotech in 1987: "A lot of faculty members were very negative about it. A couple of them didn't want me to get tenure."[5] Langer is a chemical engineer who brought an engineering design approach to biology and pioneered in the fields of tissue engineering, regenerative medicine, and controlled drug delivery. In addition, he cofounded Moderna, the messenger RNA (mRNA) innovator. He is known as "the Edison of Medicine" for his 1,400 issued and pending patents worldwide—and he has founded forty biotech firms.

Langer doesn't believe that there was a single breakthrough moment when attitudes changed. "I think it just became gradually more accepted because more and more people did it," he says.

Today, many academic life sciences leaders expect and hope to spend time at biotechs at some point during their careers, helping to translate their research. The barrier between the academic upstairs and the commercial downstairs has been largely erased.

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Arguably, none of this would have happened without *the remarkable level of support of health science research at and from NIH.* Funding for other research and development (R&D) agencies pales in comparison to the support that the health research powerhouse has built, reaching, as previously noted, $45 billion in 2022. The political role of the disease groups that back "their" institutes at NIH has translated into gains for NIH's overall budget and bipartisan political support in Congress. In contrast to the NIH juggernaut, the physical science–oriented agencies—which have never built the political support base that health research has enjoyed—have faced funding stagnation.

Overall, there has been a virtuous cycle of developments that has led from science to technology, creating both a strong life sciences economic technology sector and powerful medical advances.

UNDERLYING MEDICAL INNOVATION SYSTEM PROBLEMS

That's the good news. But there are storm clouds in the drug development process that must be faced.

First, there's *the requirement of blockbuster-size markets* for new drugs. Because the cost of developing a new drug or device that can meet FDA approval is so high, and the time so extended, only drugs that can command a major market are undertaken.

The cost of developing a new prescription medicine that receives FDA approval has risen to $2.6 billion, according to one study based on a review of 106 drugs.[6] That includes out-of-pocket costs for drug development and clinical trials of $1.4 billion and a time cost (the expected return that investors forgo while a drug is in development) of $1.2 billion. That total figure represents an increase of 145 percent over a decade. And since the typical drug development company is working on a portfolio of drugs, only a few of which will actually obtain approval, the gains of the successful drugs must offset the development costs of the majority that fail. That means that a new drug must command a market that significantly exceeds the development costs.

In such a system, drug and device companies are forced by financial necessity to develop products only for blockbuster-sized markets. This model leaves out most diseases prevalent primarily in the less-developed world, most infectious diseases, and drugs for diseases with small populations of patients (so-called orphan drugs).

Some have suggested that 90 percent of the world's medical R&D is spent on 10 percent of the diseases.[7] While this may be overstated, it illustrates the problem. The optimal drug from an economic return perspective is one that treats a problem but doesn't cure it, requiring massive annual expenditures by the individuals with the affliction for a lifetime. The economic tilt is toward drugs like Viagra, not the new antibiotics that we need as resistance to existing drugs grows in dangerous bacteria.

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On top of this, *the movement toward personalized medicine* presents an added problem. There is widespread acknowledgment that our "one-size-fits-all" approach to medicine, based on broad population averages, often breaks down because all our individual genetic makeups, conditions, metabolisms, and other characteristics differ in important ways that affect health. Many drugs help only a small portion of patients with a particular disease. With research advances, we may now be better able to tailor solutions to reflect the variability among patients. Personalized or precision medicines could enable more targeted, predictable, and effective healthcare customized to each patient.

If a medical solution must be personal to individuals, though, how are these specific drugs going to move through the FDA approval process? Will each personalized medicine require a unique approval process and separate clinical trials? And what will a workable economic model look like for individualized solutions, given that the blockbuster drug model clearly does not fit?

The problems are exacerbated because of the country's litigious nature. The *threat of litigation* is a constant problem for drug makers, who become risk averse and less willing to bring new technologies through the FDA approval process.

All of this is unfolding in the context of a *looming cost trainwreck for government healthcare spending*. Overall US healthcare spending grew 9.7 percent in 2020, reaching $4.1 trillion total, or $12,530 per person.[8] The inflation rate in health has long far exceeded the inflation in the rest of the economy; in 2005, per-capita healthcare spending was $6,040. Of those trillions, 2020 *public* spending on healthcare totaled $2.09 trillion, exceeding the $2.04 trillion in private spending.[9] Healthcare expenditures that year took up 19.7 percent of US gross domestic product (GDP)—nearly a fifth of the total economy.[10] While some of the federal share was from increased expenditures for the COVID-19 pandemic, the government share has been converging with the private share over time. With the government share of American health costs now at more than half, it resembles a socialized sector.

The federal government is not prepared for the oncoming demographics of an aging population and its corresponding health costs. Most of the federal budget now goes to social benefit programs, including healthcare programs (Medicare, Medicaid, and the State Children's Health Insurance Program), Social Security, and other safety net programs, with the costs of health programs continuing to rise much more sharply than other federal programs. The Congressional Budget Office data suggest that healthcare spending will continue to climb as a percent of the total federal budget, approaching 30 percent by later this decade.[11] The US has long been more tax resistant than other developed economies; if federal taxes reach more than 20 percent of GDP, there tends to be major political resistance. Increases in federal health spending alone will be pushing

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the federal government to increase taxes well over the 20 percent of GDP threshold in coming years. That's because Government Accountability Office projections suggest that if federal taxes are kept below the 20 percent level, federal revenues will soon be sufficient to cover only interest on the debt, health and social benefit spending, and defense, and it would be insufficient to cover the federal government's general nondiscretionary spending.[12]

The cost of healthcare is beginning to reach the point where the federal government can't sustain its commitments, which does not bode well for a continuing federal role in healthcare innovation. While innovation that solves problems should cut costs, the record suggests that the increase in medical innovation, because it is focused more on treatments than cures, has actually been *adding* to costs.

All of these issues present significant problems for the future of the medical innovation system.

THE NATIONAL ACADEMY OF MEDICINE CRITIQUE OF THE NATIONAL INSTITUTES OF HEALTH

In 2003, the National Academy of Medicine (then called the Institute of Medicine) issued a noted study on the NIH that remains quite relevant.[13] The study found that with changing demographics, changing patterns of illness, and the increased possibility of pandemics and biothreats, NIH needed to alter its organization. With twenty-seven separate institutes and centers, NIH was fragmented and unable to respond quickly to emerging health threats. The report also expressed concern about NIH's ability with this structure to manage fundamental new science challenges. Noting that NIH had been relentlessly allowing Congress, encouraged by patient groups, to add new entities to NIH, it found that it was time to end this proliferation and aim at better cross-agency management capability. Despite the number of separate program boxes at NIH, the report recommended that NIH focus instead on building its *overall* capabilities.

Clearly, eliminating institutes and centers would embroil NIH in major political battles with the same disease groups that had spearheaded the agency's growth. However, the report found that the NIH's organization was "not only imperfect," but also that no one would have ever designed it this way at the outset had the implications been known.[14] It recommended emphasizing modifications focused on enhancing NIH's ability to pursue "time-limited strategic objectives that cut across all institutes."[15] Given the inherently conservative nature of the peer-review process that NIH uses to make its research award decisions, the report concluded that NIH needed to pursue "a special ability to undertake more high-risk, high-return projects."[16]

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Of course, the report recognized capabilities at NIH. Its decentralized structure across many institutes and centers, and its bottom-up system of researchers applying for awards, set the research agenda without centralized priorities—which allowed many diverse R&D priorities to be pursued. But these also had disadvantages. Investigator-initiated awards may miss critical health research priorities. And the plethora of highly independent institutes and centers limits the ability to pursue health challenges common across a group of them. A strength of the NIH is its basic research capability, but its inability to pursue applied research as well can be a problem. In general, changes on the health frontiers required organizational change.

The report made specific recommendations, including the following:

- Centralize management; there are too many management layers. This would mean more authority for the NIH director to enable increased responsiveness, great flexibility, and more opportunities for coordination.
- Force justifications for adding any more boxes to NIH's already unmanageable structure.
- Strengthen NIH's clinical research program with more public-private partnerships and a new center program to improve this.
- Engage in strategic planning across NIH's many stovepipes to allow cross-cutting initiatives.
- Set aside 10 percent of NIH's budget for these cross-cutting efforts based on the cross-agency strategic plans. These planning steps could be reconsidered every two years, and they would be multiyear and time-limited, with additional staff in the director's office to help jump-start them. The strategic planning and cross-agency efforts should be controlled by the director's office.
- Create a Defense Advanced Research Projects Agency (DARPA) equivalent at NIH for high-risk, high-payoff, highly innovative projects that often do not survive the peer-review process. Award decisions would be made by project managers, not peer-review committees. It should be funded at $1 billion or more a year, and enable rapid review and initiation of promising projects, given the lengthy process for typical NIH grants.
- NIH's intermural program should be improved, with more program metrics and accountability.
- NIH's data and information systems should be standardized so that institutes, centers, and researchers can draw on each other's databases and common metrics can be established.
- Limit the terms of NIH institute and center directors, and require an annual review of the performance of each institute and center.

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- Shift the independent authority and status of the National Cancer Institute so it would fit better into NIH.
- Improve funding for better research management.

This systematic criticism of NIH was unique at the time, given its history of congressional backing, and was resented by many in its academic researcher community who were major beneficiaries of its ever-expanding research funding.

There were some changes at NIH in response to the report—Congress stopped adding new structure boxes to NIH and gave the NIH director a modest fund to sponsor cross-cutting research—but most of the recommendations have not been done. Harold Varmus, a former director of NIH as well as the National Cancer Institute, once commented that NIH would be more efficient and manageable if it had a far smaller number of larger institutes organized around broad science areas.[17] That step has not been taken.

INNOVATION SYSTEM PROBLEMS AT THE NATIONAL INSTITUTES OF HEALTH

NIH makes a good case study because a number of the innovation system lessons of prior chapters can be applied. Building on the Academy of Medicine study and concepts for science organization in prior chapters, some innovation system gaps are highlighted next.

First, *NIH is not a connected organization*. Divided into its twenty-seven stovepiped institutes and centers, the agency has great difficulty connecting research across them for common benefits and to build research mass in key areas that show promise. It is true that in 2004, the former NIH director Elias Zerhouni created a "road map" program supported by a common fund authorized by Congress for cross-agency collaborations on science advances that affected multiple institutes, but it remains modest.[18] There is little research coordination with other health organizations such as FDA, the Centers for Disease Control and Prevention (CDC), DARPA's Biological Technologies Office, or Army Medical Research.

During Barack Obama's administration, the Office of Science and Technology Policy (OSTP) tried to alter this with a series of cross-agency initiatives—beginning with the Brain Initiative, which brought together four agencies—but coordination is still quite limited.[19] For example, FDA is a regulatory agency, not a research agency, and its regulatory approach is increasingly falling behind the technology curve of needed advances to make it more efficient and effective. NIH is devoted to a "drug only" approach and has not built a significant focus on the science and technology research needed for improved regulatory processes. As medical technologies become increasingly complex,

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FDA's reviews take ever longer and the costs multiply. NIH has had only a very limited collaboration with FDA around regulatory science needs. These disconnects affect health innovation.

Another gap is that *NIH does not undertake connected science*. It's not enough to connect across agencies; it's also important to connect across stages of technology advance. NIH is a basic research agency with few mechanisms in place to enable handoffs between the research that it sponsors and the later stages needed for technology development. Research awards overwhelmingly go to academics, not companies, so there is no hybrid model in place to foster links between university researchers and firms.

Applied programs are largely missing from the NIH research portfolio. NIH does have a Small Business Innovation Research (SBIR) program that allocates a small portion of NIH research funding for company research awards. It does have a National Center for Advanced Translational Research (NCATS), formed in 2011, which focuses on the technology translation process to overcome barriers to implementation and the use of new treatments and health solutions, in recognition of the gap in this area at NIH.[20] But these programs are located in NIH stovepipes and have difficulty operating across the agency.

Fortunately, the development of the biotech model out of university research, and the robust relationship between venture capital and biotechs, have offset this connected science problem to some degree. But NIH could be more efficient if it spurred more translation into later stages through its programs.

Further, *NIH does not pursue a convergence approach.* NIH is organized around biology. Biology funding dominates its research portfolio, and its staff and grant review panels are composed largely of biologists. It tends to be all biology, all the time. Medical advances increasingly stem from a mix of fields, joining life, physical, engineering, and computational sciences. NIH has had difficulty adequately embracing this convergence research model. (There is more on convergence later in this chapter.)

In addition, *NIH does not pursue a challenge model for research advances*. NIH is a bottom-up organization from which individual researchers seek funding for their own research priorities. It awards a vast number of small research grants to principal investigators at universities. NIH does not create research strategies.

As Susan Hockfield, a neuroscientist and the former president of MIT, once put it to me, NIH's strategy is to let a thousand flowers bloom. Sometimes, though, she added, it becomes necessary to plant flowers in a garden.

NIH's approach means that it doesn't organize its research portfolio around consensus strategies to solve health science challenges. Instead, these are addressed indirectly by individual researchers pursuing their own priorities. There is an important role for

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researcher-initiated basic research, of course, but that doesn't necessarily need to be the only approach.

The NIH process is moves slowly. NIH's grant applications and approvals can take more than a year, which can help ensure thoughtful consideration through peer review. But the review process, coupled with its decentralization, can be a problem in the face of acute health problems, such as infectious diseases and biothreats where more rapid response is required. For example, many consider NIH's slow response to the AIDS epidemic in the early 1980s to have led to a failure to curtail the spread of the disease and, correspondingly, to numerous deaths.[21] (On the other hand, the NIAID's Vaccine Research Center acted with great alacrity during the COVID-91 pandemic.)[22]

NIH's peer review process tends to avoid high-risk, high-payoff approaches. Peer review has many virtues, assuring a competitive process and the funding of the high-quality research that has been a bulwark of the nation's strong research program. It does, however, have some disadvantages. For instance, it is now well understood than when the award ratio of applications to grants reaches more than 4 or 5 to 1, the committee process for peer review tends to become more cautious, with funding going to incremental approaches rather than higher-risk breakthroughs to better assure at least some progress in a research area. NIH has made attempts to set up separate categories to consider and evaluate higher-risk research to allow it a level of support, but further efforts along these lines may be required.

For decades, *NIH has had difficulty tackling new science opportunity areas*. For example, nanotechnology has great promise for health science, enabling the delivery of therapies directly into cells. NIH, though, was slow to fund nanotechnology research, while the NSF, a far smaller research agency, for years invested much more heavily in nanotechnology opportunities. NIH's emphasis on drug research and its focus on biology tend to curtail advances in other fields such as bioinformatics, which remained underfunded for a significant period. NIH's creation of NCATS and a bioengineering institute constituted attempts to reach emerging science areas, but again, they are modest stovepipes with limited budgets in a decentralized agency.

THE CORONAVIRUS PANDEMIC ILLUSTRATES THESE ISSUES AT THE NATIONAL INSTITUTES OF HEALTH

While the efforts of OWS in approving and deploying vaccines were a vital success (as discussed later in this chapter), the pandemic that hit the US and the rest of the world from 2020 through 2022 saw repeated failures at NIH, as well as at other health agencies that confronted the crisis. The CDC, for example, created public confusion with

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its mistakes in messaging about masks, its failures in developing testing, and by recommending prioritizing most of the population for vaccines rather than staging them to emphasize the elderly. The FDA's slow and cautious approach to approving initial booster shots, even though mRNA allows rapid development, may have limited vaccine protection for a time for many, particularly older people. There were also a number of breakdowns at NIH.[23]

NIH's cautious approach through its peer review process to supporting higher-risk medicals breakthroughs meant that it failed to support mRNA vaccines through the 1990s and into the 2000s, when Katalin Kariko and Drew Weissman, biochemists at the University of Pennsylvania, were struggling to make the foundational discoveries that would create the field of mRNA therapeutics, and they received only limited support for work that proved pivotal.[24] Fortunately, DARPA did focus on mRNA as a means to develop rapid vaccines, and in 2013 it began funding early work at Moderna and other companies into mRNA for vaccines. However, when DARPA tried to interest NIH in needed mRNA follow-on research, it was rejected because the technology was considered too risky and unlikely to materialize.[25]

NIH did, much later, support work at NIAID's Vaccine Research Center (by Barney Graham, Jason McLellan, Kizzmekia Corbett, and their colleagues) to stabilize the coronavirus spike protein, which was a key to enabling effective vaccines.[26] But years for potential advances were lost because of NIH's limits in pursuing new science areas. NIH's emphasis on funding slower, safe, and incremental studies through its conservative peer-review process, as opposed to higher-risk, breakthrough research, is a culprit.

NIH's slow pace in funding research grants is another problem that undermines innovative research. NIH received $5 billion in additional funding during the pandemic to pursue COVID-19 research. Long COVID research—on the serious long-term health problems faced by COVID victims—has been notoriously slow to get moving.[27] By 2022, about 7.7 to 20 million Americans, according to the CDC, suffered from long COVID—a health emergency by any definition. Information on the frequency of long COVID, who is at high risk, the extent that vaccines provide protection against it, and better information on how to prevent and treat continuing cases is still desperately needed. Yet only 9 of the some 240 registered and pending long COVID studies were funded by NIH by June 2022.

Congress allocated $1 billion to NIH for long COVID research, but NIH's plan to create a research consortium with 200 patient study recruitment sites resulted in less than 15 percent of the necessary participants being enrolled. In contrast, Britain's Recovery trials in 2022 were yielding important insights about long COVID using less than

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$3 million in funding to enroll 47,000 patients almost immediately. The Recovery research also identified the steroid dexamethasone as the first drug to improve survival for hospitalized COVID-19 patients, saving some 1 million lives worldwide.

NIH funds predominantly drug development, but other areas, and a convergence-type approach, can be vital. During the pandemic, behavioral research became critical to understanding how to reach millions of Americans who refused to be vaccinated and the many who were vaccinated but then rejected boosters. Francis Collins, the agency's director during the pandemic, acknowledged that NIH had made a profound under-investment in behavioral research: "I never imagined a year ago when those vaccines were just proving to be fantastically safe and effective, that we would have 60 million people [unvaccinated]."[28]

After years of the pandemic, major questions remain about how best to prevent and treat COVID-19.[29] NIH is still the largest funder of clinical trials, but pharmaceutical and medical device companies now support some six times as many trials as NIH. NIH support for trials in nonblockbuster drug areas, such as infectious diseases, fills a critical gap, but NIH has been retreating from clinical research. The Infectious Disease Society of America (ISDA) guidelines in June 2022 for treating hospitalized COVID-19 patients cited forty published clinical trials on which treatments could be based.[30] Only a handful were generated by NIH. CDC and FDA in the US relied again and again during the pandemic on British, Israeli, and Danish studies—not NIH studies—for key findings about prevention and treatment.

Of course, despite these problems, NIH got many things right during the pandemic. The work of the Vaccine Research Center, as noted, was exemplary, Dr. Anthony Fauci, NIAID's director, was a level-headed spokesperson during the pandemic for many, despite the sometimes chaotic approaches of Donald Trump's administration. NIH-organized vaccine trials worked well even in the face of the agency's declining focus on this area, and the insistence of Collins that vaccine makers include a significant portion of minorities in vaccine trials helped assure these populations of the vaccines' safety. But the problems identified here remain.

WHAT THE PROBLEMS OF THE NATIONAL INSTITUTES OF HEALTH TELL US ABOUT INNOVATION ORGANIZATION

Problems in NIH's organization, and the challenges that NIH faced in the pandemic, offer an instructive illustration of the "innovation organization" points made in previous chapters, including on connected organizations, connected science, the value of

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challenge models, speed in addressing problems, and alternatives to peer review, all of which are relevant here. In addition to the innovation organization issues, there are important "legacy sector" features that the NIH embodies that require consideration.

NIH is a classic Vannevar Bush pipeline, organized around "technology push." But the organization and the innovation system that it supports suffer from a number of the characteristics of legacy sectors outlined in chapter 7.

First, the *perverse cost structure* that NIH-fostered technologies face is based on a blockbuster model that limits the ability of treatments for small-population, rare, and infectious diseases to scale up into products. On top of that, NIH's *established institutional architecture*, with too many disconnected institutes and centers, creates a barrier to additional innovation. *Politically powerful vested interests* depend on NIH's current decentralized and divided structure and emphasis on small investigator-initiated grants, including disease groups and academic researchers, which has limited the ability of Congress, the executive branch, and NIH's own leadership to reform its organization.

Add to this that NIH's *established knowledge and human resources structure* is locked into a biology framework that limits the ability of technologies and approaches from other sciences to contribute to advances. And the conservative and cautious results from NIH's biology-oriented peer review process have created an inability to pursue adequate levels of high-risk, breakthrough research and an *aversion to innovation.* Further, the high and growing cost of FDA reviews and approvals required for drugs and devices to enter the market has led to *unmanageable transaction costs* for many smaller companies trying to serve markets that cannot absorb the development costs.

These all amount to legacy-sector barriers to innovation and must be overcome to smooth the pathway to innovation.

THE GENOME WARS ILLUSTRATE THE NIH INNOVATION ORGANIZATION ISSUES

The "genome wars" were waged between the NIH's Human Genome Project and organizations led by Craig Venter.[31] They ran a race, between 1990 and 2000, to be the first to sequence the human genome in a highly publicized rivalry that led to highly productive results (as detailed in chapter 5). The episode illustrates some of the challenges in NIH's innovation organization.

NIH faced a set of challenges in this competition that required it to reorganize its genome project repeatedly to meet them. When Venter was at NIH in its neuroscience institute, he was required to pursue only the genomes for the brain, illustrating the stovepipe organization problems at NIH. When Venter departed from NIH, he built

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an integrated interdisciplinary team with deep expertise not only in molecular biology, but also in computers. Team members all knew each other, traded ideas, and met frequently to solve problems.

NIH had trouble creating a comparable interdisciplinary group. Venter had developed a way to process hundreds of genes through express sequencing tags (ESTs), and the group developed other key processing advances enabled by supercomputing, particularly whole-genome shotgun sequencing. In contrast, NIH's genome project initially relied on numerous funding awards to university research groups, which only occasionally yielded fruit. As it became clear that Venter's team, working off a carefully developed technology development strategy, was far ahead of the NIH group and expanding its lead, the new NIH leader, Francis Collins, reorganized. To reduce the group to a manageable size, he sharply cut the number of universities involved. Taking lessons from the Venter team's progress, the NIH group adopted the new processing technologies and what we now call "bioinformatics advances" being developed by Venter's team.

While Venter's group built what was then the third-largest supercomputer, NIH, lacking computer prowess, turned to the US Department of Energy (DOE), which in 1986 had suggested and begun the genome project because NIH wasn't interested,[32] for its supercomputing power. So NIH had to abandon its biology-only orientation and incorporate DOE supercomputing. As Venter's group continued to progress, NIH cut down further its participating schools, focusing in particular on an MIT group built by Eric Lander, a mathematician with strong computer know-how. This much smaller NIH group pressed ahead and began to get within range of Venter's group, building on the approaches that his group had figured out. Finally, the two teams negotiated a solution in 2000;[33] they published their working drafts of the human genome sequence, covering more than 80 percent of the human genome, in leading science journals on the same day. A near-final draft of the human genome, 99 percent complete, was published by NIH in 2003, with a final version published in 2021.[34]

The competition led to a much earlier sequencing of the human genome than otherwise would have occurred, and to processing and bioinformatics advances that were later continuously improved to enable ever cheaper and faster genome processing. It helped lead to the new fields of genomic medicine, bioinformatics and database analytics, and the potential of personalized medicine. It was one of the most productive competitions in life sciences history.

At best, NIH would have achieved these developments at a much slower pace without the forced competition and example from Venter's group. Therein, we find some important lessons for NIH: its normal structure and approach were unable to accommodate

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the radical genome sequencing model; a streamlined, centralized, team-driven, multidisciplinary effort was required, working on the "challenge" model through a directed technology strategy.

THE HEALTHCARE DELIVERY PROBLEM: EXAMPLES OF ANTIBIOTIC RESISTANCE AND FDA REGULATORY SCIENCE

There aren't just problems with the health science innovation system through organizational issues at NIH. The structural issues run much deeper.

"BAD BUGS, NO DRUGS"

The Infectious Diseases Society of America (IDSA), a leading US medical organization, issued a report in 2004 (since updated). It was aptly titled "Bad Bugs, No Drugs: As Antibiotic Research Stagnates, a Public Health Crisis Brews."[35]

Antibiotics curtail the risk of infection, a major medical problem. Beginning in 1942, for example, it was antibiotics that dramatically reduced the risk of death from pneumonia, then the nation's largest killer among diseases. They also make many other medical procedures possible, including joint replacement, transplantation, cancer chemotherapy, and premature newborn care. But as the IDSA has noted, there has been a rapid rise in antibiotic resistance since 2000 because of antibiotic overuse in people, animals, and the environment in general, exacerbated by a breakdown in the development of new antibiotics.

The CDC released an updated threat report in 2019 estimating that at least 2.87 million antibiotic-resistant infections occur annually and at least 35,900 people die in the US every year due to antibiotic-resistant infections—that is, one person every 15 minutes.[36] If deaths related to the bacteria *Clostridioides difficile* are included, the annual total comes to more than 3 million. The CDC, in estimating the *C. diff* threat alone, found that *one in eleven people over age 65* diagnosed with a healthcare-associated *C. diff* infection dies within one month.[37] The CDC estimated in 2010 that in the US, approximately 99,000 deaths related to healthcare-associated infections occur every year,[38] and there has been only limited progress since then.

The IDSA found, based on FDA data, that few new classes of antibiotics have been developed in the past three decades, and at least one of those already faces antibiotic resistance. Thirty years is the typical time frame for resistant strains to rise to 60 percent resistance.

While overuse of antibiotics has exasperated the problem and requires controls, the heart of the problem is still that the pipeline for new antibiotics has been drying up.

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There are few antibiotics in the drug pipeline, and the existing number of antibiotic agents that do what they're intended to do is dropping because of resistance. Antibiotic research is lengthy, with a high risk of failure, and the cost of bringing a new drug to market through FDA phases and approvals, plus the monetary cost over time, is very high, in the $2 billion range, as discussed earlier. Because antibiotics work so well so fast, they produce a weak return on investment; from a purely financial point of view, successful antibiotics are too successful to justify the investment costs. There is a structural market failure in our drug development innovation system that is already leading to a public health crisis.

INNOVATION STAGNATION

In 2004, the FDA issued a report with a startling title: "Innovation/Stagnation—Challenge and Opportunity on the Critical Path to New Medical Products"; it has since been updated in a number of follow-on reports.[39] The 2004 report identified a number of problems with innovation in medicine: a slowdown in innovative medical therapies reaching patients; a pattern of breakthrough basic discoveries that were not yielding safer, more affordable medical products; a complex, inefficient, and costly medical development path; a decline in proposals for new drugs and biologics submitted to the FDA for approval; dramatic increases in the costs of medical product development; a drop in the number of innovative medical device applications submitted to the FDA; and innovators concentrating on blockbuster drugs because of high development costs. In turn, as suggested at the outset of this chapter, developing products to meet high public health needs was becoming increasingly difficult, including for less-common diseases, diseases found mostly in the less-developed world, prevention indications, individualized therapies, and biothreats.

At the center of the problem was a finding that the FDA's applied science for medical product development was not keeping pace with basic science advance. More pointedly, this means that if federal R&D investment is in basic science at NIH and not in the follow-on evaluation and review process, there will be problems in the medical innovation system. NIH's efforts to develop new science were unrelated to technology development and review. There was little applied science work on creating new tools for obtaining better answers on safety and effectiveness with faster time frames, more certainty of findings, and lower development costs.

The report indicated that the FDA—which, it should be noted again, is a regulatory agency, not a research agency—was in sore need of a new development toolkit, with new scientific methodologies in applied areas, new animal models or, better yet, computer-based predictive models, new biomarkers for safety, and new clinical evaluation techniques. The FDA had long played a key role in setting standards, but it needed more

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modern science for this, including a new generation of performance standards and predictive tools.

Unfortunately, the FDA's own initiatives to tackle these challenges—its Critical Path and Regulatory Science initiatives and its "big data" analytics for improving clinical trials—have been underfunded. NIH, with the needed levels of research funding and with its biology (not regulatory) agenda, has not developed a significant research portfolio to help tackle these problems, and the FDA is not resourced to undertake them adequately. The result has been a continuation of the structural problems and corresponding market failures in the medical innovation system.

These IDSA and FDA reports suggest that legacy-sector issues not only affect NIH but stretch across the healthcare delivery system. These legacy barriers include a perverse price structure for healthcare that is based not on performance but quantity of services; an institutional architecture that resists change; vested interests that defend the existing paradigm; an established knowledge base that tends to be locked in through established professions; resistance to change in the health delivery and innovation system; institutional obstacles at the government level such as those discussed previously at the FDA and NIH; and a "network economy" problem wherein large-scale networks of institutions and actors limit the adoption of change.

Despite these system barriers, health science innovation remains dynamic in many ways. A new research entity, such as a DARPA for health, offers the promise of an alternative means to advances.

DOES HEALTH SCIENCE NEED A DARPA?

President Joe Biden's administration in 2021 proposed an Advanced Research Projects Agency for Health (ARPA-H) modeled on DARPA,[40] which was funded by Congress at $1.5 billion in 2022. The idea was not new. Robert Cook-Deegan, a close observer of the early years of the Human Genome Project, wrote a 1996 article proposing a DARPA for healthcare. He noted some of the DARPA characteristics reviewed in chapter 6, including expert staff, a focused mission, ability to exploit new ideas rapidly, only two layers of management, entrepreneurial program managers empowered to line up the best talent groups they can locate, and engaged, interactive relationship with grant recipients.

Peer review is not the only way to award research grants, as Cook-Deegan emphasized and as noted earlier in this chapter. DARPA's alternative of strong program managers making selections allowed much lower transaction costs. The group processing under peer review is often too cautious. If there is only a 15 to 20 percent selection rate, reviewers find it difficult to differentiate the truly outstanding from the merely excellent,

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leading to more conservative selections and ruling out high-risk and high-reward proposals. DARPA's pursuit of specific technology challenges cut down on wasting researchers' time; with NIH's open solicitation approach, for instance, researchers would often have to prepare four or more detailed grant applications for every award received.

Cook-Deegan cited examples of NIH's problems with risk-taking from his experience with and study of the NIH genome project. The DOE had begun the project years before NIH was ready to consider it, for example, and in 1981, NIH turned down Leroy Hood's plans to automate genome sequencing, so Hood had to obtain funding from the NSF. Overall, peer review avoided risk-taking and was limited in its ability to pursue breakthroughs. It was not simply a matter of improving administrative efficiency and lowering review budgets, but the DARPA model could be better at pursuing mission-oriented science advances. A DARPA model could look more like Venter's effort than NIH's original genome project. In addition, DARPA's ability to fund both small and large grants depending on the nature of the challenge gave it more flexibility in pursuing effective research approaches than NIH's reliance on small grant awards. Including a DARPA model in health research could get around some of the problems in NIH's organizational model that impeded making progress on major health challenges.

In addition to a new agency offering a different innovation organization approach, new ways of organizing health research are beckoning. Convergence provides an instructive example.

CONVERGENCE

The postwar period witnessed major advances in the life sciences. The first was a revolution in molecular biology, which seeks to understand the molecular basis of biological phenomena and activity in and between cells, including molecular synthesis, modifications, and interactions, as well as the ability to affect these interactions. While earlier experiments provided underpinnings for this field, molecular biology emerged from bringing physics into biology, led by Max Delbruck and Salvadore Luria, Nobel Prize winners who had physics training—including from the physicists Niels Bohr and Enrico Fermi. The ability to study disease at the molecular particle level led to major health research progress.

A second revolution was in genomics. Built on advances in molecular biology and the discovery by James Watson, Francis Crick, and Rosalind Franklin of the structure of DNA, it concerns the structure, function, and mapping of human genes, as well as the interactions of the genes with each other and with other elements. The human genome initiative that sequenced the human genome allied computational science with biology.

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Molecular biology and genomics were both medical research revolutions relying on interdisciplinary thinking.

Building on the disciplinary mergers behind both molecular biology and genomics, "convergence" is the merger of biology with physical, engineering, and computational sciences for a new research model.[41] The biochemist and Nobel Prize winner Phillip Sharp and the bioengineer Robert Langer, winner of both the National Medal of Science and the National Medal of Technology, have argued that convergence amounts to a third medical research revolution.[42] This involves scientific fields not only communicating with each other, but also integrating at the research bench.

The NSF defines convergent research as "driven by a specific and compelling problem." It requires "deep integration across disciplines," with "experts from [those] different disciplines pursu[ing] a common research challenge"—a process in which "their knowledge, theories, methods, data and research communities increasingly intermingle." From this can emerge "new frameworks and paradigms or even "disciplines," as they "adopt a new scientific language."[43] Fields such as synthetic biology, computational biology, regenerative medicine, tissue engineering, nanobio, and bioinformatics are all convergent; all rely on combining other scientific disciplines with biology. Of course, convergence is a concept and research model that can apply beyond the life sciences, but that is our focus here.

Susan Hockfield, as noted earlier, has called convergence "the scientific story of the century," adding that "a century ago physics and engineering came together and transformed our world and now biology and engineering are poised to transform our future as profoundly."[44] She argued in an interview that

> physics starting around 1900 decoded the parts list of the physical world . . . subatomic particles—electrons, protons, neutrons—as well as X-rays and other forces that connect and organize the components of the parts list of physics. With elements in hand the electronics industry was born and then its successors, the computer and information industries . . . But truth be told, biology was far behind; before around 1950, biology had not yet revealed its parts list. We didn't know what the components were. Biologists were describing the behavior of biological organisms—they didn't know what the fundamental controlling parts were. But the revolution in molecular biology, beginning in the late 1940s and continuing today, revealed biology's parts list, it led to the discovery of DNA and RNA and the understanding that these molecules carried the information to build proteins, the workhorses of biology. Engineers are now using this parts list to build the technologies that to my mind will be the miracle technologies of the twenty-first century.[45]

The idea behind what Hockfield calls "the next technology revolution" in the "age of living machines" is that change will be driven by the combination of molecular biology and genomics methods and knowledge bases with a systems biology approach that incorporates a new engineering design model and toolset, along with the physical

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science. It brings in engineering not simply for devices and computation, but also for technology design. It joins the biological model of complex, dynamic, interactive systems with engineering design prioritization and targeting. It means merging biologists, engineers, and physical scientists at the research bench level.

While NIH has been slow on the uptake, a number of universities have significant programs at the time of this writing, including MIT, Stanford, University of Chicago, Harvard, Georgia Tech, University of Michigan, and Northwestern. Over one-third of MIT engineers, for example, now undertake biology-related research. The list of engineering tools that come into convergence play is a long one, including

- Targeted nanoparticles for delivery across cell walls and membranes
- Polymer nanoparticles and quantum dots for treatment delivery
- Next-generation magnetic nanoparticles for multimodal, noninvasive imaging
- Implantable, biodegradable microelectromechanical systems, including lab-on-a-chip devices, for in vivo molecular sensing of tumor-associated biomolecules
- Low-toxicity nanocrystal quantum dots for biomedical sensing
- Computational modeling of complex systems

While the molecular biology and genomics revolutions essentially built new knowledge bases, the entry of engineering through convergence means new therapies plus knowledge bases. Tools for imaging, sensors, nanotechnologies, simulation, modeling, probability, and artificial intelligence (AI) mean that a complex systems biology model joins an engineering design model.

Could convergence-based strategies improve healthcare? An MIT report provides case studies of potential examples.[46] For cancer, convergent approaches could include, for example, minimally invasive methods of early detection to make treatment far easier, nanotechnology-delivered cancer vaccines, as well as new drug delivery methods that can deliver multiple drugs to a cancer, deliver two different therapies in a controlled and sequenced punch, or deliver fragments of RNA that silence a cancer gene. For infection, synthetic biology tools give researchers a potential means to monitor a wide variety of phenomena in cells and use that information to modify cell activity, such as by initiating or shutting off the production of a protein. For brain disorders, new methods for seeing deep into the brain, based on chemical engineering techniques, are helping researchers build more detailed, three-dimensional maps of neural circuits, and large-scale genetic sequencing and sophisticated data processing are leading to the identification of subtle genetic differences in people with schizophrenia; this could provide biomarkers for early diagnosis and, therefore, early treatment of a range of neuropsychiatric disorders. These are only a few of many examples.

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One massive problem with healthcare delivery, as noted earlier in this chapter, is its cost. The cost problem is significant in part due to the lack of any incentives for cost control; the federal programs that increasingly dominate healthcare are fee-for-service, where the incentive is to add services and thus increase costs. Past efforts at healthcare cost reform have focused on altering the financial plumbing and have missed an innovation system focus. Could convergence-bolstered innovation drive down costs by improving health?

As the MIT report noted, these healthcare fiscal trends will become unmanageable over time without significant breakthroughs in early lower-cost diagnosis, prevention through lifestyle changes, and novel treatments, which convergence approaches offer.[47] Convergence, with its multipronged offense, holds the promise of better health solutions, not just incremental treatment improvements.

There have been promising convergence-based approaches in health. During Barack Obama's administration, the White House developed the Brain Initiative[48] and initiatives for Precision Medicine, including the All of Us initiative, aimed at building large-scale patient health databases to take advantage of data analytics,[49] which were multidisciplinary and cross-agency. DARPA formed a new Biological Technologies Office in 2013, organized around a convergence model. NIH's NCATS was founded to undertake translational research, including convergent approaches. The NSF, as noted earlier, has an explicit convergence focus in its research. And more than fifteen universities are actively pursuing this convergence approach, organizing research centers and programs around it.

As the great funder of health research, NIH will need to play a key role. An occasional initiative is not enough; it will need to support programs and pooled funding for convergent research across its stovepiped institutes and centers. It will need to develop a strategy based on challenge models for key convergent advances that include cross-agency personnel and experts from outside NIH and outside biology. Peer review will need reform, with review panels that include engineers and physical scientists. More multiprincipal investigator grants that bring in researchers across fields will be needed for larger-scale awards that are multidisciplinary. NIH will also need to sponsor education programs so the needed disciplines can educate each other and develop a common research language and approaches. ARPA-Health could play a significant role.

THE IMPORTANCE OF INTELLECTUAL PROPERTY IN LIFE SCIENCES

In chapter 2, we treated intellectual property as an indirect innovation factor—important to innovation, but not as crucial as the direct factors. But in the life sciences field,

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intellectual property is a more direct linchpin for innovation. Intellectual property rights—patents—place control over innovation in the hands of the innovator, creating a legal framework that gives the patent holder a monopoly, for an extended period, over the innovation. It has proved a powerful incentive that rewards the very innovation that lies at the heart of society's technological, and therefore economic, advancement. If you remove the incentive for people to undertake the high risks, major time commitments, and heavy costs of innovating, you erase the ultimate innovation.

In physical science–based fields, there are often a variety of technology avenues to reach a technology advance, but that has tended to be less the case in the life sciences, where much of the innovation ecosystem is organized around patenting. This explains, in part, why (as discussed earlier in this chapter) the life sciences have been able to attract longer-term investment in earlier-stage innovations than physical science–based innovations. This ability to attract early-stage capital means that investment will cover the extended development time and high costs of new drugs and medical devices. Of course, investors require that these costs be recaptured, which explains why patents underpin the entire system: biotechs and pharmas and their investors have to be able to recapture their heavy development costs in order for the innovation system to work. Again, new drug development and years of clinical trials typically cost close to $2 billion and take more than a decade, and the great majority of new drug ideas fail. A twenty-year patent term is key to making all this innovation juggling work.

Of course, there are pricing abuses from this patent monopoly, and corresponding problems caused by the focus on the blockbuster drug model, as previously discussed. But the loss of breakthrough health innovations could be the price of disrupting life sciences patenting by eliminating patent rights or introducing price controls for innovative drugs. European controls on drug price controls have driven much of the innovation side of drug development (and the corresponding economic benefits) to the US, which in the past generally avoided these steps.

The early stages of life sciences research are largely undertaken at universities, with NIH funding. But through the 1980 Bayh-Dole Act,[50] universities acquired the patent rights to the intellectual property developed from the federal science research that they undertook. In many cases, using this intellectual property, these researchers became the leaders of new biotech firms. The patents could also be licensed. While the federal government retains the ability under Bayh-Dole to march in and retake the patent, it has never done so—wisely, many think—and innovation has flourished.

There are, though, some complicating signs ahead. The high cost of many new drugs has created strong political opposition to pharmaceutical companies. In 2021,

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during the pandemic, the Biden administration broke with precedent and sought to waive intellectual property rights held by Pfizer, BioNTech, and Moderna for the mRNA vaccines under the Trade-Related Aspects of Intellectual Property Rights (TRIPS) international agreement, arguing that it would increase global supply. The companies had frantically manufactured hundreds of millions of vaccine doses and planned to soon produce billions more, with Pfizer and its partner, BioNTech, delivering them to low- and middle-income nations at cost, but the government's position held. Ironically, the limits to further global supply lay in the supply chain, not in the producers.[51] (Another side of the pandemic innovation story is set out in the next section.)

In addition to the TRIPS waiver, the Biden administration sought, and Congress in 2022 passed, provisions to regulate for over the next decade the cost of 100 leading drugs for which Medicare pays.[52] The effects on the health innovation system remain to be seen.

OPERATION WARP SPEED

Past American industrial policy approaches were crisis-driven, but OWS, a response to the coronavirus pandemic, faced a crisis on steroids. OWS was an industrial policy approach new to the healthcare field.[53] It has been acknowledged as a major accomplishment, thereby showing its potential.[54]

At the beginning of 2020, when the highly infectious and deadly COVID-19 virus landed in the US, the public health system was dangerously unprepared for the scale of the assault. Much of the nation's vaccine and medical supply industries had been outsourced abroad. The CDC's early failure to develop a sound test for the coronavirus and get it produced became a notorious signal of the nation's lack of preparedness.[55]

In vaccine production, the number of US vaccine makers had declined between 1970 and 2003 from more than thirty to a mere five firms[56] because preparing a vaccine that is used only during, or to prevent, an epidemic is not a lucrative market. Companies want to sell blockbuster drugs that people must take for life, not vaccines that are taken in a few doses and largely solve the problem, and have a large market only if much of the population is facing a disease disaster. So much of vaccine production had shifted abroad, with India becoming the largest vaccine producer and China growing fast and hoping to dominate the sector. This exacerbated the preparedness problem.

OWS brought together the US Department of Health and Human Services (HHS), DOD, CDC, FDA, NIH, and other agencies in a partnership to develop, manufacture, and distribute effective vaccines against COVID-19. It was a wholly governmental, cross-agency partnership, directed at and with participation from the private sector. And it was a public

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health triumph, delivering hundreds of millions of doses of new vaccines at an unprecedented speed—a year, not a decade—and saving an estimated 2.3 million lives in the US.[57]

The various elements of OWS offer lessons that can be incorporated into other initiatives aimed at taking on major health challenges. First, there was a *strong government team*. Since there is no substitute for talent, the mix of talent and agency expertise involved in OWS was an important indicator of its success—it operated as a change agent in the system.[58] It was conceived by Dr. Robert Kadlec, HHS assistant secretary for preparedness and response, joined by Dr. Peter Marks, director of the FDA's Center for Biologics and Research. Marks' Star Trek fandom led him to name the new organization "Warp Speed."

OWS resembled a company, with an interagency board, but was a government operation that brought in officials, as needs arose, from key health agencies such as the FDA, CDC, and NIH; DOD agencies, including the Army Corps of Engineers and DARPA; and HHS agencies, such as the Biomedical Advanced Research and Development Authority and the Administration for Strategic Preparedness and Response. None of these agencies individually had the breadth of authority needed to develop and deploy the needed vaccines rapidly, so OWS was set up as a new entity, combining authorities from across the agencies involved. Including leaders from each helped assure cross-agency coordination. There was also significant industry experience in OWS's leadership group.

Dr. Matthew Hepburn, a former DARPA program manager and OWS's DOD lead for vaccine development, has said: "Warp Speed was inspired by DARPA but with a focus on scaling and implementation. OWS was DARPA at scale."[59] He was referring to DARPA's reputation for sponsoring technology breakthroughs, finding top talent, providing fast implementation, and avoiding bureaucratic lethargy. OWS exemplified a series of industrial policy approaches.

The next crucial element was the *active involvement of companies*. Effective industrial policy requires both an active and creative governmental role and willing and energetic company participants. If companies are neither committed to a project's goals nor ready to invest in them, the project will not work. In OWS, the government was able to work with committed leadership at committed companies such as Moderna, Pfizer, and the latter's partner BioNTech.[60]

A crucial part of the work with companies was the *integration of federal personnel with the private-sector firms*. While OWS was a government-run enterprise, it integrated its staff with private-sector companies. This began early and continued throughout the effort. OWS put federal agency personnel into certain companies to help them with the complex regulatory approval processes and assist with project management and supply access. This integration did not compromise safety or the process—the federal employees remained federal personnel—but eliminated bureaucratic barriers and accelerated processing.

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To get to a vaccine quickly, a *portfolio approach* was key. OWS had the great advantage of many years of prior research on mRNA applications,[61] and by the time COVID-19 arrived, mRNA was approaching scientific readiness—but had never received the resources needed to scale.

OWS didn't want to rely solely on mRNA, which had not yet led to an approved vaccine, so it took another page from the DARPA playbook and decided on a portfolio approach. It surveyed more than 100 pending vaccine projects, decided on three types of vaccine technology platforms—some new, such as mRNA, and others more established—and then picked two companies to support each platform approach. It developed a portfolio to manage the technology risk, selecting a range of technologies and firms.[62] For mRNA vaccines, OWS selected Moderna, led by chief executive officer (CEO) Stéphane Bancel and Hamilton Bennett, its senior director of vaccine access and partnerships;[63] and Pfizer, the major pharmaceutical, led by CEO Albert Bourla, which teamed with BioNTech, led by CEO Ugur Sahin and chief medical officer Ozlem Tureci.[64]

Guaranteed contracts were tremendously important in moving the OWS work forward quickly. Once the firms were selected, OWS began targeting them with support. One key was the issuance of contracts for the production of their vaccines, even though the vaccines had not yet received emergency-use approval from the FDA. The OWS concept was that further vaccine development and clinical trials would proceed in parallel with actual vaccine production so doses would be ready for distribution as soon as they were approved. The contract guarantees enabled the companies to manage the development risks.

In addition to the guaranteed contracts discussed here, OWS employed *flexible contracting mechanisms*, including making extensive use of the Other Transactions Authority (OTA) that DARPA had first developed. For DARPA and other DOD agencies, OTA has provided a much faster and more flexible way to contract outside the glacial process of typical federal procurements. Contract agreements using OTA can be reached in days, not months, and for OWS, they were key to working with biotechs and smaller suppliers unaccustomed to complex federal contracting.

Once vaccines were ready, *technology certification* figured in the success of OWS. The FDA's Emergency Use Approval (EUA) was a key to speed. EUA allows the FDA to meet emergency health needs without patients having to wait for the full and permanent approval that often takes years of reviews. This FDA step was vital: it amounted to a certification and validation of the technology, ensuring instant market acceptance.

As previously noted, FDA approval is the gold standard for medical products worldwide, and it signifies that products work. Medical practitioners and the majority of the American public promptly accepted the vaccines as soon as they received the FDA's EUA.

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Such rapid, emergency technology certification is completely unavailable for other US nonmedical technologies, but the pandemic story shows how important they can be.

Even with approvals, though, there were major *manufacturing and supply chain* challenges to be addressed. In theory, the government's guarantee that it would purchase the vaccine at scale was crucial to enabling firms to take the risk of ordering supplies and developing rapid production facilities. But it was not that simple. By the time COVID-19 hit, the US had offshored much of its medical production capability. It had nearly stopped making masks, personal protective equipment, glass vials, swabs, and diagnostic tests. When the pandemic hit, the US was completely unprepared and had to start relaunching production capabilities for those products in the face of collapsing exports from other countries focused on meeting their own needs.[65] The CDC had never focused on supply chain problems.

Pfizer had US as well as European production capacity, which, once it had a guaranteed federal contract of $2 billion for 100 million doses (contingent on the FDA granting EUA for its vaccine), could be applied to the mRNA vaccine developed with the German company BioNTech. But the smaller biotechs, including Moderna, had limited manufacturing experience. So OWS intervened, building or refurbishing production plants, purchasing and fitting out equipment, hiring staff, enabling raw material supplies, and purchasing vials, syringes, and needles in bulk.[66] The Army Corps of Engineers oversaw construction to expand company production facilities.[67]

The Defense Production Act (DPA) figured here. The legislation, which allows the federal government in national emergencies to require suppliers to supersede serving their customers in order to meet security needs, dates back to the Korean War. It proved key to lining up supplies and resources for vaccine makers to avoid production delays, once there was in-depth understanding of every facet of relevant supply chains.

DOD, accustomed to supplying US troops in the post-9/11 wars, had a strong emergency logistics capability and knew the importance of supply chain reliability and flexibility and how to map them. It sprang into action, helping the companies with these supply issues and working to manage the application of the DPA to get key supplies to vaccine makers while not disrupting other needed markets.

DPA, of course, can be a double-edged sword. It needs to be applied carefully to avoid disrupting other important markets.

OWS also took on the task of organizing a *distribution system* and getting the doses of the vaccine shipped to states based on a state population–based formula. OWS's DOD staff led the way, integrating vaccine development with distribution to local sites and developing a computer tracking system to manage it. It relied on close collaboration with major private-sector firms to handle delivery, including McKesson, UPS, and FedEx, and

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used major pharmaceutical chains CVS and Walgreens, which had the outreach to get vaccines to the most vulnerable elderly. Considering that the two mRNA vaccines had to remain frozen and required special complex handling, the logistics were remarkable, with only a tiny amount of vaccine ending up spoiled in shipment.

Vaccine distribution, however, did not mean actually getting the vaccines into people's arms. While OWS originally expected the military would create mass vaccination sites and administer the shots, state public health bureaucracies insisted that administration was their role—and OWS acceded. But the state health bureaucracies were not ready, and doses administered initially lagged far behind doses delivered to those who were supposed to be giving people shots.[68] But after these initial rollout problems, which the Biden administration made a priority to fix, the doses administered scaled up to meet the demand by March 2021. In the end, the US led vaccine development and distribution, weeks ahead of its European Union (EU) counterparts.

The distribution lesson here concerns taking advantage of private-sector distribution systems and networks through a close-knit public-private partnership. Another lesson for future emergencies is that local public health systems need to be better prepared.

OWS was an *operation*, not science research itself. The work on the science and the technology development behind it had been undertaken in the years before the pandemic. OWS was about scaling up a technology into manufacturing and getting it to users rapidly—something that the federal government simply had not done before, except in defense areas.

The federal government has systematically ignored American manufacturing decline. It has paid little attention to processes for scaling up new technologies and their related products. It has developed few tools to undertake these steps. OWS worked only because military approaches to scale up were systematically applied by a flexible new organization that reached across agencies. As OWS's Hepburn pointed out, it was like a DARPA for scale-up, with an industrial policy approach.

All the elements just discussed—diverse talent, guaranteed contracts, flexible contracting mechanisms, committed companies, technology certifications, mapped supply chains, federal officials integrated with companies, and distribution systems—could be considered to tackle other critical national needs, including future medical emergencies. A number of these could also be employed to help close gaps in medical innovation, such as for small-population diseases, vaccines, and antibiotics. Although the Biden administration dismantled OWS when it assumed office, thus scattering the expertise that OWS created in how to undertake these steps, the operation still stands as a model for additional capabilities that could be deployed in the future.

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PERSISTENT CHALLENGES

NIH has gotten many things right, but there are persistent problems in health innovation. The requirement of blockbuster-size markets limits medical progress in small-population and developing-world diseases, antibiotics, and vaccines. Personalized medicine lacks a workable economic model, and there is a major threat to the entire system from rapidly growing federal healthcare costs. NIH's stovepiped organizational structure, with its twenty-seven institutes and centers, means little collaboration on common challenges takes place. It doesn't undertake efforts that connect science to development; it has avoided convergence approaches linking biology to physical and engineering science fields; it is slow-moving on its grant awards; its peer review system avoids high-risk, high-reward projects; and it is difficult for it to pursue new science areas across its stovepipes. Although it eventually reorganized to achieve it, NIH's difficulty in scaling up the Human Genome Project speaks to many of these problems.

By itself, addressing how NIH is organized will not resolve the many issues that confront health innovation. In general, healthcare delivery is a complex, established legacy sector, locked into a set of problems that limit the ability to introduce new advances. There are deep problems in, for example, pursuing antibiotic resistance, which is a growing threat. We need to develop the science that will improve the FDA's regulatory speed and capabilities, as another example.

Some of the recent challenges point to opportunities. The new ARPA-H could fill some of the gaps in the NIH system, presenting new options. The convergence movement to integrate biology with physical and engineering sciences, while a challenge to NIH's biology focus, seems to promise major new advances. And OWS provided an example of new toolsets that could be employed to meet medical challenges.

Health innovation, with the right innovation organization built through the steps identified in prior chapters and explored here, could lead to dramatic gains.

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9 CASE STUDY: THE ADVANCED MANUFACTURING CHALLENGE

Robert Solow developed the field of growth economics, as discussed in chapter 1, by demonstrating that what he termed "technological and related innovation" was the dominant causative factor in economic growth.[1] It had taken economics two centuries after the publication of Adam Smith's *Wealth of Nations* to identify this long-invisible behemoth in the classical economics parlor: a demonstrated theory of economic growth.

But as discussed at the outset of this book, there was a problem. Solow found that economic growth was exogenous to the approaches of his still-dominant school of neoclassical economics. The variables behind innovation were simply too complex to fit within the metrics-driven neoclassical theories of the twentieth century. While mainstream economics focused on markets because they can be modeled, it was unable to model the group of complex factors behind economic growth that lay outside the market system as such.

The central concept of mainstream economics is that dynamic equilibrium: market signals drive meeting points between supply and demand, such that even as change is constant, the net consequence remains equilibrium. Innovation-based growth, however, is a dynamic system that is not, and cannot be, in equilibrium. Features such as the organization of innovation systems simply did not fit with supply and demand curves.

Of course, an economics school without a functioning theory of growth appeared unacceptable to many, and a group of "new growth theory" economists, initially led by Paul Romer (as discussed in chapter 1), worked to make growth theory endogenous—in other words, to place it into an analytical, neoclassical box.[2] But this has proved to be such a difficult problem that many economists have sought more manageable and measurable projects, such as developing behavioral economics.

Its inability to grapple with innovation systems has left economics in a particularly difficult situation when it comes to analyzing the American manufacturing sector.[3]

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Manufacturing, and especially the initial production of new technologies, must be seen as part of the innovation system. It is a creative stage in which a new product must evolve through prototyping, product definition, and production design, from an idea into a good that can be both produced and marketed. This often requires a thorough reexamination of the underlying science behind the innovation, as well as a huge dose of innovative engineering, to develop a workable, durable, competitive technology that can be produced at a cost and priced at a level to allow it market entry.

But despite its prowess in the second half of the nineteenth and first half of the twentieth centuries as the world's manufacturing giant, the US has not viewed manufacturing as part of innovation. Coming out of World War II, when Vannevar Bush was forming the boundaries for new research and development (R&D) agencies (as discussed in chapter 3), the focus was not on manufacturing, where the US had far larger capacity and output than any other nation. Bush placed the focus on science research, where the US had been weak coming into the war compared to Germany and Britain. In 1945, manufacturing was the last area that the US needed to worry about; it was the manufacturing king, with a system of mass production to which no other nation came close. Innovation became defined as R&D in the US, with the manufacturing stage ignored.

Over time, the delinking of innovation from production has increasingly put the US at a competitive disadvantage. Many other better-known factors play into the problems of the American economy, but the drag that comes from ignoring the innovative power of manufacturing techniques has been hugely important, too. Whatever the reasons for the oversight—the biases of neoclassical economics; the path dependency effects of the post–World War II "pipeline" model that emphasized federally funded research universities and basic research; and other factors—we have paid a price in social stability and economic and national security for ignoring this critical connection.

MANUFACTURING DECLINE

American manufacturing has, indeed, been in decline.[4] While most Americans believe the US has to lose manufacturing to low-cost producers in Asia because we have high wages, Germany's manufacturing experience tells a different story. Its manufacturing wages are much higher than in the US, and yet manufacturing accounts for twice as large a share of German gross domestic product (GDP) compared to US GDP, and Germany runs a massive manufacturing trade surplus, including with Asian nations. Germany kept a strong manufacturing ecosystem for its manufacturers that closely ties innovation and production; it undertakes collaborative R&D between small and large firms and university engineering; and it has a world-renowned skilled manufacturing workforce.[5]

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Its system of more than seventy Fraunhofer Institutes is a public-private partnership that brings together large and small manufacturers and engineering universities with government cost sharing and effectively pursues each of these tasks. Some 20 percent of the German workforce can be found in manufacturing, compared to 8 percent in the US. The US, unlike Germany, faces a number of gaps in its manufacturing innovation system, as discussed next.

LAGGING PRODUCTIVITY

Between 2000 and 2010, the US lost about a third of its manufacturing jobs. Government data shows output decline in that period in thirteen of nineteen of the manufacturing sectors measured; in three, growth was behind GDP growth; and in two more, computing and energy, output was significantly overstated.[6] Only 18 percent of manufacturing jobs had come back by 2017; and even by 2018, US manufacturing output was still below its prerecession 2007 level.[7]

The output problem is reflected in productivity levels; the US manufacturing productivity rate is lagging key competitors.[8] While US manufacturing productivity was increasing by an average of 2 percent per year from 1992–2004, it declined into the 1 percent range or less after 2004.[9] Small and midsize manufacturers (i.e., those with fewer than 500 employees) in particular are falling behind: there is a growing gap in productivity between small and large manufacturing firms.[10] Behind those low productivity numbers are corresponding low levels of capital investment. The fixed capital investment of manufacturing in areas such as plant, equipment, information technology (IT), and others actually declined 1.8 percent in the 2000s when adjusted for cost—the first time that this occurred since data collection began in 1947. It declined in fifteen of nineteen industrial sectors in that period and continues to be at relatively low levels.[11] This low investment is particularly pronounced at small and midsize manufacturers.[12] While there has been a surge of manufacturing capital investment in 2022–2023, it is largely in only two sectors, semiconductors and batteries, and led by investments by foreign, not US, firms.[13]

Job loss data signal a hollowing sector, with 64,000 factories closing from 2000 to 2013.[14] The low productivity level is a sign of an underlying innovation system problem. For example, US manufacturing-related patents lag far behind those of China.[15]

A THINNED-OUT ECOSYSTEM

While the US once had firms and supply chains organized in a more vertically integrated system, a financial model of short-term returns with a focus on "core competency" led firms to go "asset light"[16] and to a thinning-out of the industrial ecosystem,[17] including its shared best practices in production and training across supply chains.

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Increasingly, as political economist Suzanne Berger found, small and midsize manufacturers were increasingly "home alone."[18]

A SCALE-UP PROBLEM

While there are many industrial sectors, there tend to be three kinds of manufacturing firms. Large multinationals, the first category, are generally strong; they are global, need to be in international markets, and increasingly have been producing abroad. Small and midsize manufacturers, the second category, produce some 46 percent of US output[19] but have had trouble obtaining financing to scale innovation. To survive, they tend to be risk averse, thinly capitalized, and perform little R&D, so have trouble implementing innovation despite their importance to overall productivity and output.[20] And while the US relies on entrepreneurial start-ups, with venture capital (VC) financing to bring innovation into its economy, VC is increasingly focused on returns from software, services, and biotechs. The number of new manufacturing start-ups, the third category, steadily declined between 1990 and 2019.[21] Hardtech firms that plan to manufacture received only 5 percent of VC funding investments in 2015, and the problem continues: this prevents them from scaling their innovations.[22]

DISCONNECT BETWEEN INNOVATION AND PRODUCTION

In the US, as noted previously, it is R&D that is seen as the innovation system, not manufacturing. Yet innovation as a *system* is more than just R&D; it encompasses all the stages through, and including, production stages; failure to understand production as a key part of this system is a fragmented view.

A strong innovation system is crucial to the US advanced economy; a technology strategy that is disconnected from manufacturing advances leads to a broken innovation system. Industry still supports two-thirds of US R&D,[23] but there is already evidence that firms losing market share to trade cut innovation activities and investments.[24] Production, especially the initial production of a new technology, requires very creative engineering and, typically, reconsideration of the underlying science in dense feedback loops—leading to final design and production. If it wants to keep pioneering new technologies, the US will need the accompanying manufacturing strength as well.

WEAK WORKFORCE EDUCATION

The workforce itself cannot be ignored as one of the gaps. After US manufacturing lost 5.8 million jobs in the 2000s, it became increasingly difficult to attract workers to manufacturing.

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Small and midsize manufacturers report that workforce issues are a growing priority.[25] The entire system is upskilling; the jobs lost in manufacturing in the 2000s were largely in lower-skilled fields, and skilled workers are now needed.[26] Baby boomer retirements and tight labor markets have been exacerbating regional manufacturing skill shortages. Simply put, the US labor market is broken; sound markets require access to sound information, but the US labor market lacks both an information system to help employers and employees navigate it and a system for effective skills training.[27] If the US is to move into advanced manufacturing, there is no effective system at this time for educating the workforce in the advanced skills that it requires.[28]

To summarize, the following are the critical gaps faced in the US manufacturing innovation system:

- A low rate of introducing new technologies, and therefore low productivity
- A supporting manufacturing ecosystem that has thinned out
- A scale-up problem for larger Main Street firms and start-ups
- Delinked innovation and production
- A lack of access to innovation for the smaller firms that control much of output
- An inability of manufacturing start-ups to scale up
- A weak, highly decentralized workforce education system

THE "INNOVATE HERE/PRODUCE THERE" DILEMMA

The disconnect between innovation and production has led to a growing problem. Since World War II, the US economy has been organized around leading the world in technology advances. It developed a comparative advantage over other nations in innovation and, as a result, it has led all but one of the significant innovation waves of the twentieth century.[29] The US led innovation in aviation, electronics, space, computing, the internet,[30] and biotech, although it played catch-up with Japan on high-quality manufacturing. Its operating assumption was that it would innovate and translate those innovations into products. By innovating here and producing here, it would realize the full spectrum of economic gains from innovation at all the stages, from R&D to demonstration and test beds, to initial market creation, to production at scale, and to the follow-on life cycle of the product.

That "innovate here/produce here" model and the full spectrum of gains that it created worked—the US became the world's richest economy. For the past two-thirds of a century, it has been playing out economic growth theory—that the predominant factor

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in economic growth is technological and related innovation—and demonstrating that it works.

In the last few decades, though, with the advent of a global economy, the "innovate here/produce here" model no longer holds. In some industrial sectors, firms can now sever R&D and design from production. Codable IT-based specifications for goods that tie to software-controlled production equipment have enabled this "distributed" manufacturing.[31] While manufacturing once had to be integrated and quite vertical, firms using the distributed model can innovate in one country and produce the results elsewhere. The model has shifted to "innovate here/produce there."

This distributed model appears to works well for many IT products, as well as for commodity products—although a major lesson from the COVID-19 pandemic is that it can create a major problem with supply chain resilience. Apple is the standard-bearer for this model, leading dramatic IT innovations but outsourcing virtually all its production to China.

Imported content is about 20 percent of the value of output for the typical US firm.[32] Overall, only some 53 percent of US domestic demand for manufactured goods is met by goods made in the US. Most computer and electronics products are not "made in the USA": 72 percent of domestic demand for these products is met by foreign imports, including Apple iPhones.[33]

However, there appear to be many sectors where the distributed production model doesn't work well—sectors that still require a close connection among research, design, and production. Supply chains for domestically located manufacturing firms still remain largely domestic, indicating a link between design and production.[34] US firms making capital goods, aerospace products, energy equipment, and complex pharmaceuticals appear to be examples of this phenomenon. In these sectors, production and R&D/design are the yin and yang of innovation—the production infrastructure provides constant feedback to the R&D/design infrastructure.

These examples suggest that product innovation—incremental advance—is most efficient when linked to manufacturing processes. However, if R&D/design production must be tightly linked to production in many sectors, then the earlier innovation stages—R&D and design—may have to follow production if it moves offshore. This may lead to *produce there/innovate there,* which may be even more disruptive than *innovate here/produce there*. The high percentage of US demand for manufactured goods met by foreign production noted previously suggests this evolution of innovation offshore, where the foreign firms are able to link R&D/design and production. The foreign firms are responding to a US failure to do so too in numerous sectors.

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These twin developments—*innovate here/produce there* and now *produce there/innovate there*—bring the economic foundations of US innovation-based economic success into question. It means that innovation investments not tied to manufacturing won't lead to full-spectrum economic gains. It also brings into question the future of US innovation leadership—it increasingly may have to follow manufacturing offshore.

There is an underlying point here. Manufacturing is part of the innovation system and must be factored into the analysis of the strengths and weaknesses in specific innovation sectors. Any governmental role in innovation must consider the steps beyond the research stage, but the US has tended to delink production from its R&D system—and this has weakened the nation's innovation capability.

TRADING PLACES

The US is running a massive trade deficit in manufactured goods; it rose to $1.06 trillion in 2021,[35] including a deficit of $244 billion in advanced technology goods in 2022.[36] These are startling numbers, and they are in significant part a story of the rise of China's economy.

China moved from 5.7 percent of global manufacturing output in 2000 to 19.8 percent in 2011, passing the US that year as the world's largest manufacturing power. Since then, the gap has widened further. Manufacturing value-adds in China were $3.85 trillion in 2020, compared with $2.34 trillion for the US.[37] The US share of world manufacturing value-adds declined from 18.1 percent in 2010 to 16.8 percent in 2019, and the decline throughout the entire period was primarily against China's growing share, which rose to 28.7 percent in 2019.[38] Goods exported from the US to China totaled $124 billion in 2020; goods imported from China to the US. totaled $434.7 billion.[39] The only historical comparison to China's three-decade rise to manufacturing supremacy was the rise of US manufacturing in the late nineteenth and early twentieth centuries.

What happened to lead to this stunning turnabout? Experts argue that China attained its number-one output ranking through a combination of price advantages, exchange rate advantages, and—in particular—an extremely fast growth rate in the physical volume of manufacturing value-adds. What's behind that last characteristic? Many have assumed China's rise is due to low production costs from cheap labor and cheap parts. There is also an assumption in the US that manufacturing must naturally migrate to low-cost producers and the knowledge required for production processes is relatively trivial and readily replicable. Neither is true. Further, there are assumptions that production knowledge flowed solely via multinationals from the outside into China, and that the IT revolution enables the severing of manufacturing from

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R&D, product definition, design, branding, and marketing, which China has taken advantage of.

Yet, as Jonas Nahm and Edward Steinfeld argue, none of these factors explains China's rise.[40] Instead, they find that China has forged a new link between process innovation and manufacturing, and its form of innovative manufacturing specializes in rapid scale-up and cost reduction. China has joined together previously unparalleled skills in simultaneous management of tempo, production volume, and cost, which enables production to scale up quickly with major reductions in unit cost. This capability has allowed China to expand even in industries that are highly automated or not on governmental priority and support lists, despite the limited labor cost advantage or government subsidies. So low labor costs and government subsidies and support are not sufficient to explain China's success in manufacturing.

China has also developed production processes that were previously considered in developed nations to be fully mature and thus impervious to further cost reductions or technological improvements. The key to this ability to innovate new production processes has been the ability of Chinese firms to accumulate firm-specific expertise in manufacturing through extensive, multidirectional, interfirm learning, taking advantage of international know-how from multinationals and building on it. For example, in wind turbine production, Chinese firms rapidly absorbed lessons from international competitors and then modified them to create designs to fit their own markets; created production systems fully capable of established production capabilities; nurtured cutting-edge technologies, such as advanced aerospace designs for blades; drew on materials science and systems engineering in production that could be both labor and capital intensive; and rapidly scaled up production.[41]

Nahm and Steinfeld conclude that the elements of China's emerging production model include (1) backward design—the ability to take existing products and create cheaper models that can better fit low-cost Chinese markets; (2) partnerships that use foreign designs joined with Chinese production, which has enabled multidirectional learning about production; and (3) technology absorption and collaborative development across networks of regional production firms, allowing rapid scale-up.[42] These are innovative manufacturing capabilities that cannot be discounted.

To multiply these new production efforts, China has long provided massive government subsidies for new plants, equipment, direct company support, and other resources to scale up its evolving industries.[43] It also created a new kind of public-private equity funding—guidance funds—for scaling up production in a range of key technology areas.[44] This enabled the country not only to develop and adopt new process steps but also to make their impact widespread quickly, amounting to a new innovation for rapid-scale

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capability. The very-large-scale subsidies alone were not enough, as Nahm and Steinfeld argued, but they were an enabler for the potent mix of production innovations.

WORKFORCE DISRUPTION

The labor profile derangement caused by this economic shift has resulted in growing social disruption.[45] Most Americans once assumed that they were becoming one big middle class, as defined socially in the popular imagination, if not according to formal economics; instead, the fact that a major percentage of Americans are actually part of a working class is now clear. And this working class has been facing declining incomes and economic frustration.[46]

Much of disruption occurred in the first decade of the twenty-first century; full-year employment of men with high school but not college degrees declined from 76 percent in 1990 to 68 percent in 2013.[47] The share of those men who did not work at all went from 11 percent to 18 percent over the same period. The median income for men without high school diplomas fell by 20 percent between those years, and for men with high school diplomas or some college but not degrees, it fell by 13 percent.[48]

Men had long dominated the production workforce, so the decline of American manufacturing in the 2000s hit them particularly hard—and the trend has continued. For example, the median annual wage in 2021 for a full-time worker age twenty-two to twenty-seven with a high school diploma was $32,000. For a full-time worker with a bachelor's degree in that age group, it was $56,000. The $24,000 difference was the highest pay gap on record since such data were first collected in 1990.[49]

Overall, real household income largely stagnated for most Americans between 1999 and 2020. This reflects a growing gap between *median* real household income—the statistical center of the middle class—and *average* real household income, which includes the higher gains going to the upper-middle and upper classes.[50] This spells middle class decline.

It also spelled growing income inequality. The noted labor economist Richard Freeman found in 2016 that American economic inequality had fallen to developing country levels, and the problem continues.[51] It can be traced in part to the stagnation in college graduation rates since the mid-1970s: workforce skill requirements kept growing, but educational output, as state support of higher education waned, failed to keep up.[52] Those who had attained higher education captured a wage premium; those without it did not. Meanwhile, the one-third decline in manufacturing jobs in the 2000s, which often tended to be better paying, exacerbated the inequality split as the definition of the middle class shifted over time. While that wage inequality narrowed with tight labor

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markets post-COVID, it remains very significant.[53] In other words, too many in recent decades have found that the loss of their manufacturing jobs led them out of the middle class.

The manufacturing decline curtailed what had been a critical pathway to the middle class for working-class families. This wasn't just a white working-class problem: African Americans make up 10 percent of the manufacturing workforce and Latinos 16 percent; the decline restricted a pivotal middle-class route for those communities.[54]

The massive trade imbalance in manufacturing hit many industrial communities especially hard.[55] Those areas that faced direct impacts from Chinese imports sustained an average annual income loss per adult of $549 between 1990 and 2007. This was offset by per-capita federal adjustment assistance of only $58. Job loss to trade with China has been estimated at 3.7 million between 2001 and 2018.[56] As the Nobel Prize–winning economist Michael Spence has reported: "Globalization hurts some subgroups within some countries, including in advanced economies . . . The result is growing disparities in income and employment across the U.S. economy, with highly educated workers enjoying more opportunities and workers with less education facing declining employment prospects and stagnant incomes."[57]

THE SIGNIFICANCE OF MANUFACTURING EMPLOYMENT

Over the past fifty years, manufacturing's share of US GDP shrank from 27 percent to 12 percent. For most of this period (1965–2000), manufacturing employment remained constant at about 17 million; in the decade from 2000 to 2010, it fell by almost a third, to under 12 million, recovering only a bit by the beginning of 2022, to 12.5 million.[58] All manufacturing sectors saw job losses between 2000 and 2010, with those most prone to displacement from globalization—led by textiles and furniture—suffering massive losses.[59]

Employment in the manufacturing sector can be viewed as an hourglass.[60] The narrow point of the hourglass, at the center, is the production moment. But manufacturing employment is not subsumed by that moment. Pouring into the production moment is a much larger employment base that includes those working in resources, those employed by a range of suppliers and component makers, and the innovation workforce—the roughly 60 percent of scientists and engineers employed by industrial firms. Flowing out of the production moment is another, larger host of jobs in distribution systems, sales, and maintenance (both within and beyond the main production company) of products over their life cycles. The employment bases at the top and bottom of the hourglass are far larger than at the production moment itself.

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Arranged throughout the hourglass are lengthy and complex value chains of firms involved in the production of the goods, from resources to suppliers of components to innovation, through production, to distribution, retail, and the life cycle; it is a great array of skills and firms, much of which we count as services. But these services are tied inextricably to manufacturing; remove the production element, and the value chains of connected companies snap. While the lower base of the hourglass, the output end, may be partially restored if a foreign good is substituted for a domestic one, the firms involved will still be disrupted. The upper part of the hourglass, the input end, with its firms and employees, doesn't get restored by import substitution. One economic study of manufacturing value-adds indicates that when the full hourglass effects are considered, manufacturing may amount to a third of the economy.[61]

Once these complex value chains are disrupted, it is difficult to put them back together. That's why, historically, once the US loses an economic sector, it tends not to come back. We also lose the potential to innovate in that sector. This is a key reason why manufacturing decline is so consequential.

There are consequences for a nation that has been a leader in innovation—including its production element—failing to retain that production leadership. The US suffered significant social disruption when it missed the quality manufacturing paradigm introduced by Japan and, more recently, from innovation in rapid scale-up introduced by China. The failures disrupted the American working class and thinned out its middle class.

WHAT MAINSTREAM ECONOMICS HAS GOTTEN WRONG ABOUT MANUFACTURING

Economics has long held an elevated position in US national policymaking—the president has a Council of Economic Advisors, not a Council of Sociological Advisors. Understanding how manufacturing is related to the economy as a whole is critical to all related policy processes concerning the economy. Alas, though, our understanding is fragile. Few US leaders took the developments in manufacturing described in this chapter seriously, in part because well-established economic views assured us that declines in manufacturing would be more than offset by gains elsewhere in the economy.[62]

Mainstream economists have long told us a reassuring story about economic change and the role of manufacturing in it:

- The nation was losing manufacturing jobs because of major productivity gains.
- The production economy would, in the natural course of economics, be replaced by a services economy.
- Low-wage, low-cost producer nations must inevitably displace higher-cost ones.

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- Don't worry about the loss of commodity production since the country will retain a lead in producing high-value advanced technologies.
- The benefits of free trade always greatly outweigh any short-term adverse effects.
- Innovation is distinct from production, so innovation capacity remains even if production is distributed worldwide.
- A governmental role in the production system would constitute a dangerous "industrial policy."

Each of these arguments has proved incorrect.

First, consider *productivity and job loss*. The political economist Suzanne Berger has noted that mainstream economists thought that manufacturing was like agriculture, where relentless productivity gains allowed an ever-smaller workforce to achieve ever-greater output.[63] She found that the agriculture analogy was simply incorrect: manufacturing productivity rates and output fell along with employment in the 2000s, meaning that we must look at the overall decline in the sector itself for why manufacturing lost nearly one-third of its workforce in a decade.

The US productivity growth rate is at historic lows; low productivity growth and related low investment levels signal that automation-driven productivity gains have not been the cause of manufacturing job decline. Instead, global competition, led by China's entry as the leading manufacturing power, has been the largest factor.[64] Mainstream economists proffered a false dream about productivity gains while output fell; they diverted us from the reality of tough international competition with nations following mercantilist policies.

What about the notion that *a service economy supersedes a production economy*? Success in a highly competitive world rewards nations and regions that produce complex, value-added goods and sell them in international trade. Although world trade in services is growing, world trade in goods is four times as strong. Complex, high-value goods such as energy, communication, and medical technologies make up more than 80 percent of US exports and a significant majority of imports. The currency of world trade is in such high-value goods and promises to remain so indefinitely. Gradual growth in the services trade surplus ($245 billion in 2021)[65] is dwarfed by the size and continuing growth of the deficit in goods; the former will not offset the latter anytime in the foreseeable future. And manufacturing jobs are still better paid and come with better benefits than services jobs.[66]

In addition, the production sector leads other sectors in the introduction of productivity gains, which lead to real gains in an economy, providing new wealth that can be distributed. Services are generally slow productivity adaptors. Production is also the most

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scalable factor in an economy, able to scale growth much more rapidly than service sectors that remain more face-to-face in nature. In other words, manufacturing appears to be indispensable to a modern economy and will not be superseded anytime soon by a services-only economy. Economists should stop pretending otherwise.

As for the notion that inevitability of *low-wage, low-cost producer nations displacing higher-cost ones*, the American public—reflecting mainstream economic views—has long fixated on the US economy losing manufacturing to lower-wage nations in Asia. But American economists forgot to send that memo to Germany. A 2018 study found that German companies pay much higher manufacturing wages than do US companies; Germany had some 22 percent of its GDP from manufacturing, compared to 12 percent in the US, and it has run a massive trade surplus in manufactured goods.[67]

The German experience demonstrates that there is no inherent, inevitable manufacturing employment or sectoral decline in advanced economies when they compete with lower-wage ones. An advanced economy can keep climbing the value-added ladder in both capital input and human-capital input if its public policies are designed properly.

The point from mainstream economists about the *loss of commodity production* is also wrong: developed nations that cede lower-end production do not automatically make it up in advanced technologies. Established production firms, faced with disruptive innovation, do typically cede low-margin production and work to retain leadership through incremental ("sustaining") advances in high-margin production, but the fact is that they often end up ceding those as well. This happens as the disruptive advances that allow capture of the low end (aided by lower costs and expanded customer bases) mature and enable the capture of the high end.[68]

This also resembles what entire nations go through. As noted previously, Chinese industry is not simply pursuing its low-cost production advantage but is also innovating in rapid production scale-up. Chinese process advances are integrated across regional firms and accelerate production tempo and volume, which are tied to cost savings.[69] In other words, Chinese leaders are pursuing an innovative production strategy that uses manufacturing-led innovation for competitive advantage. At the same time, US industry has allowed its historic production leadership to slip, endangering its innovative capacity in important areas of technology—again, because production cannot really be delinked from innovation. The US economy, far from leading in advanced technologies, ran, as noted, a $195 billion trade deficit in advanced technology goods in 2021, a deficit that has been growing.[70] Developed nations aren't necessarily assured of leading in advanced technologies when they cede commodity technologies.

Similarly, the *free trade advantages don't always outweigh any short-term adverse effects*. The data cited here concerning social disruption and manufacturing decline illustrate

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the reality of adverse trade effects. As noted, trade was the leading cause of manufacturing decline in the 2000s.[71] Manufacturing decline can be readily mapped; it tends to be regional, with significant effects on particular industrial communities. As Amy Goldstein's 2017 book *Janesville* shows, most sectors in communities that lose a major industrial employer tend to contract, from suppliers to indirectly related service firms.[72] The decline affects the community's tax base as real estate values drop, affecting community services like education and healthcare.

Homes are typically a family's greatest asset; if their homes are devalued, it is difficult financially for families to leave. Middle-aged workers often have extended families and generations of ties in these localities, with accompanying responsibilities that make it tough for them to bail out even if they can acquire the skills to find other work. These market frictions exacerbate social disruption; it is very difficult for affected communities and individuals to climb back, so that decline is lasting rather than only short term. The effects can be dramatic. Gains from increased trade are often offset by deadweight losses to the economy in affected regions, particularly through the rise in transfer payments for unemployment, health and disability insurance, and food stamps that are required to cope with declines in employment and real wages. These payments are compensatory; they do not reflect economically productive investments and, indeed, they make such investments harder to finance.

Back in 2004, Paul Samuelson took on mainstream economics by asking how the US could be an economic loser with a low-cost, low-wage competitor like China, despite the longstanding Ricardo-based economic theory of "comparative advantage" in trade.[73] He noted that if Chinese industry begins to make productivity-enhancing gains, coupled with a low-wage advantage, it could capture some of the comparative advantage that previously belonged to the US through its productivity dominance. Then, in a Ricardian analysis, he added that unemployment caused by trade never lasts forever, "so it is not that U.S. jobs are ever lost in the long run; it is that the new labor-market clearing real wages have been lowered by this vision of dynamic fair trade."[74] In other words, US wages would fall to a point where China's production price advantage is offset.

That appears to be correct: wage stagnation in the US was long a growing problem[75] below the upper-middle class, and growing numbers of the working class moved from middle-class incomes to lower-end, lower-paying service jobs. Wage stagnation for the working class improved in 2021–2022 with tight post-COVID labor markets, although this was partially offset by inflationary prices.[76] Overall, the US economy still benefits from lower-priced imported goods, but Samuelson fund there can now be "new net harmful U.S. terms of trade."[77]

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Dani Rodrik's 2017 book, *Straight Talk on Trade,* attacks the economics mainstream for its failure to alert the public that global trade was creating gaps in developed nations between the well educated, who do well in global trade, and the less educated, who tend to do badly.[78] The academic mainstream, he suggested, continued to articulate a theory of free trade in which the benefits are pervasive even when it is not reciprocal (where one side allows open trade and the other does not): "Economists can be counted on to parrot the wonders of comparative advantage and free trade whenever trade agreements come up. They have consistently minimalized distributional concerns . . . [Yet] the standard models of trade . . . typically yield sharp distributional effects: income losses by certain groups of producers or workers are the flip side of the 'gains from trade.'"[79]

By holding to perspectives that assumed away things such as trade-related unemployment and income inequality, Rodrik argues, the mainstream favored theory over known realities, misled the public, and blocked a focus on more realistic policies for adapting to a global economy.

Samuelson had warned years earlier that responding to trade disruption by imposing tariffs could result in economic "arterial sclerosis."[80] His alarm is reasonable; the economy, including the production supply chain, is now thoroughly globalized, and retrenchment from trade (as opposed to pushing back against mercantile practices) could be problematic. But we should stop systematically underestimating adverse trade effects and refusing to consider improved overall trade strategies and worker support.

The final point on the earlier list of misconceptions perpetuated by mainstream economists concerns *the dangers of industrial policy*. This is a debate that has raged for years, and for nearly all that time, the terms of the debate have been excessively simplified and distorted. Thus, when Japan's innovations in quality manufacturing harmed US auto and consumer electronic sectors in the 1980s, some in Congress proposed rescuing industrial losers through an industrial bank. In a well-known attack on industrial policy, the economist Charles Schultze, who had once led the US Office of Management and Budget, argued in response, as noted earlier, that the inevitable political forces driving government led it to be ill suited to carefully fashioned industrial interventions.[81]

What should we make of this seemingly eternal debate? The innovation system should certainly be spared the political pork barrel, but many important governmental interventions can stop far short of that. As the growth economist Richard Nelson states: "The conditions for a pure market organization to result in a 'Pareto optimal' equilibrium never are fully met. This is recognized, implicitly, in serious policy discussion, where the argument about policy almost never is about whether the situation actually is 'optimal,' but rather about whether the problems with the existing regime are sufficiently severe

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to warrant active new policy measures."[82] These issues are explored in more detail in chapter 12.

The beginning of wisdom when it comes to understanding advanced manufacturing is the simple but somehow elusive point that when it comes to generating growth, not all industries are created equal. Regrettably, mainstream economists have typically been unable to differentiate between the potential of different sectors. The story of the economist Michael Boskin's inability to differentiate between the production of potato chips and computer chips is an embarrassing case in point.[83] These mainstream economists have failed to see that factors such as technological capacity and its ability to generate increasing returns for an economy make a real difference. Manufacturing is the classic sector for increasing returns, and because it dominates technological development in the economy, it is a core of innovation capacity.

PURSUING ADVANCED MANUFACTURING

US industry is competing with low-wage, low-cost producers, particularly in Asia. Could it develop new production paradigms to drive up efficiency and drive down costs so it could better compete?

We have seen new production paradigms before, and we will doubtless see them again. We can, arguably, *make them happen*, too. New production paradigms can transform the production sector.[84] Creating phase changes from new manufacturing paradigms can translate into major potential growth benefits.

Innovation carries its own rewards; *production* innovation is no exception. It can enable better products, create new markets, and, just as important, generate good jobs. But while the US has R&D-led innovation, other countries have manufacturing-led innovation: Germany, Japan, South Korea, Taiwan, and now China.

The US was the first to develop interchangeable machine-made parts in the nineteenth century, and by the twentieth century, it was the leader in mass production. These new manufacturing processes were highly creative and combined new technology development and organizational and process development, joined with new business models. After World War II, the US led world production output—no other nation was even close—and assumed that the reason, the country's remarkable mass production paradigm, would mean that its production leadership would be ongoing. So, in the postwar period, it focused on an area where it needed to build its strength—the research stage.[85]

Japan's leadership of the quality production paradigm forced the US to play catch-up on quality in the 1970s and 1980s, but not to adopt a manufacturing-led innovation capability along with its R&D-led innovation. Some policy leaders have, in effect, been

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suggesting that it is time to do both, by pursuing policies for advanced manufacturing.[86] New manufacturing processes are highly creative and evolve in steps that combine new technology development and organizational and process development, joined with new business models.

Advanced manufacturing is the application of innovative technologies to improve manufacturing processes and products, adding significant value to the sector through productivity advances and innovation. Scientists and engineers now tell us that a number of new advanced manufacturing paradigms may be within range that could transform manufacturing efficiency, productivity and returns, including the following:

- *Digital production*: A mix of advanced IT, radio frequency identification, sensors, and the Internet of Things applied in every stage and element; new decision-making from machine learning and big data analytics, artificial intelligence (AI), supercomputing, simulation, and modeling
- *Robotics*: Lightweight, flexible, voice-controlled robots that can work in close proximity with workers and support their tasks
- *Additive manufacturing*: Three-dimensional-printed parts and systems that can enable highly complex and lighter shapes and geometries unavailable through regular machining
- *Advanced materials*: A "materials genome" capability, applying supercomputing to design all possible materials with designer features to fit specialized needs for strength, plus light weight and resilience
- *Biofabrication*: Includes tissue engineering, regenerative medicine, and synthetic biology
- *Nanomanufacturing*: Fabrication at the nanoscale that enables new precision and capabilities
- *Mass customization*: Production of single products or small lots at the low cost of mass production, to enable highly customized goods, enabled by three-dimensional printing and new computerized processes
- *New distribution efficiency*: Information system advances that yield efficiencies in distribution, supply chains, and connecting with customers
- *Energy efficiency:* Technologies that cut energy use in production (energy essentially being waste) to cut cost and raise efficiency

There are also specific new technology areas, such as photonics, new chemical and biopharma processes, flexible electronics, power electronics, and advanced composites, that can translate into both production efficiency and innovative products. The core idea

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behind advanced manufacturing, then, is to bring the still-strong US innovation system more directly into manufacturing. This, in turn, will require new, advanced workforce skills and corresponding training.

Developing such new integrative paradigms is the core concept behind advanced manufacturing. Advanced manufacturing institutes have been devised as a means to nurture such paradigms. Still young, they represent a major policy change to address the disconnect in the US between R&D and production. Previously, the policy issues in manufacturing concerned tax, trade, currency, and regulatory policy; innovation was not on the table. Although these other policy areas remain important, improvements in them tend to be incremental and marginal. Gains from innovation can be more dynamic, as the advent of mass production and quality manufacturing indicate. This is the first time—at least since 1987, the start of Sematech (Semiconductor Manufacturing Technology), the public/private collaboration supported by the Defense Advanced Research Projects Agency (DARPA)—that an *innovation system* approach to manufacturing has been considered.

The innovation system problems spelled out in this discussion—lagging productivity, a thinned-out manufacturing ecosystem, scale-up problems, the disconnect between innovation and production, and weak workforce education—are all structural problems in the manufacturing system that require *systems* solutions. Manufacturing, of course, is overwhelmingly in the private sector, and advanced manufacturing will be as well. Even US Department of Defense (DOD) procurement, while sizable, supports only some 8 percent of manufacturing output.[87] A government-only effort won't work; an approach that more systematically engages the private sector to address system needs is required if it is to scale up properly.

Based on recommendations from the industry-university Advanced Manufacturing Partnership collaboration begun by President Barack Obama,[88] an effort began in 2012 to use new manufacturing institutes to create new production paradigms in a range of advanced production areas, shared across the supply chains of large and small firms and across industry sectors. The approach was loosely modeled on Germany's Fraunhofer Institutes.

The advanced manufacturing institute model, a collaborative model bringing together industry, universities, and state and federal governments, now includes sixteen institutes, with three more authorized, featuring programs that reach nearly every state in most of the new technology areas listed previously. The costs of the institutes are shared among federal agencies, industry, and state governments. Each institute is designed to pursue a particular technology area, such as robotics, digital production, or additive manufacturing.

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The manufacturing institute model is promising because it brings together the three core actors needed for advanced manufacturing. For this reason, the institutes appear to be one of the right models to meet the challenge; it is difficult to envision a workable model that doesn't bring together these actors. The model attempts to deal with the gaps in the system as follows:

- Connecting small and large firms to restore the thinned-out ecosystem
- Relinking innovation and production through collaboration between firms, universities, and government
- Pursuing production innovations to grow efficiencies and productivity
- Providing shared facilities for scale-up
- Building a skilled workforce to implement and disseminate advanced production technologies into companies

The institutes have been trying to address these key structural elements missing in our system, but they require sustained federal support. Manufacturing's structural problems are long term and require longer-term leveraging from federal investments, along with continued cost-sharing by industry and state and local governments. At stake is the industrial base needed if the US is to have sustained technology leadership.

Why institutes? One key reason is that the majority of the US manufacturing sector consists of small and midsize firms that are risk-averse and thinly capitalized; they are not in a position to perform research or adopt new technologies and processes unless the costs and efficiency gains are demonstrated and understood. Although larger firms once assisted their supply chains in this role, providing a vertical integration function, they have often cut back to their core competencies in our era of intense global competition. They are, therefore, less able to assist suppliers and have their own competitive problems in adapting. Again, as Suzanne Berger put it, manufacturing firms are increasingly "home alone."[89]

Larger firms, too, need to collaborate to share the risks and costs of changing to new production paradigms. Taking a page from Germany's Fraunhofer system, institutes can act as test beds, providing a range of industries and firms with opportunities to collaborate on, test, and prove prototypes for advanced production technologies and processes.

Institutes can also help fill the talent gap. Technical workers must be trained to work with the advanced technologies and develop the processes and routines necessary for introducing them into production systems. Otherwise, they simply will go nowhere.

The key trading partners and competitors of the US spend much more at the governmental level on their manufacturing base and investing in advanced manufacturing.[90] The importance of maintaining this base in the US is increasingly being recognized.[91]

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No one actor, including the government through its contracting role, can generate all the new manufacturing technologies and skilled workers and suppliers on which it depends. Instead, we need a system in which a connected network of firms, universities, labor, governments, and national and corporate laboratories together nurture the next generation of production technologies, processes, and education infrastructure. The market alone does not support efficient levels of investment in these networks, often called a "manufacturing ecosystem" or "the industrial commons." The institute model is designed for the problem of getting to advanced manufacturing.

A restoration of production innovation leadership may prove crucial to the continued innovation leadership of the US, which it has viewed as its core competitive advantage. The public-private manufacturing institute partnership model addresses structural problems in the manufacturing innovation system, and thus is a critical route for the federal government to continue to pursue. In parallel, it mandates new training systems to implement the new technologies.

How are the advanced manufacturing institutes faring? They face several major challenges.[92] First, there is a scaling problem. Can a program that spends roughly $200 million a year in federal seed funding make a real difference in a manufacturing sector with $2.3 trillion in output?[93] The much higher investments that key competitor countries are making in advanced manufacturing, particularly China with its own much-larger network of better-funded manufacturing institutes, send a signal that US manufacturing investment levels need to move up significantly.

Second, there's a program design error to fix. At the outset of the program, the institutes were limited to five-year terms for federal support—a limit that had political appeal but created policy problems. The term limits forced them to organize around the needs of large firms, the only plausible source for funding once the five years of federal funding ran out. But a financially sustainable model based on big firms rules out engagement with the small and midsize firms that are most in need of help in adopting advanced technologies. It also contradicts the institutes' role in workforce investment—large firms can't justify investing in other firms' workforces.

Underlying all this is that manufacturing's problems are structural; they don't get fixed in five years. Long-term, sustained investment is required, and the federal role is the enabler for private-sector and state matching.

Two of the three agencies that sponsor the manufacturing institutes have been working to correct this design flaw. The US Commerce Department and DOD have undertaken a process to review their institutes after five years and, if an institute has been successful, extending its term for another five years. The US Department of Energy (DOE) has not taken this step; as a result, some of its institutes have become empty shells. Unfortunately, DOD is offering only quite limited funding for the second term for its institutes.

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Third, there is a need to create a network function across the institutes because firms will need to adopt *packages* of manufacturing technologies, not just one at a time. In other words, a company is going to want to adopt robotics and digital production and advanced sensors and other technologies in a connected way. It's much more difficult for firms to cope with adoption one at a time; a central network function would combine the advances of different institutes and package them to be integrated and interoperable for easy adoption by firms. A similar network function for workforce education in advanced manufacturing is also needed.

Fourth, the R&D system needs to be better connected with the institutes. The institutes' major task is applied technology development in their technology areas. But expanded manufacturing research in the R&D agencies is needed, and the institutes need to be linked to and help guide this research. R&D agencies need resources to build manufacturing-related R&D feeder systems (e.g., an expanded pipeline of manufacturing technologies) that align with institute needs to create more manufacturing innovation.

Finally, while the institutes have had successes in both technology development and workforce education,[94] these course corrections are needed. But there are additional gaps that must be addressed.

A significant part of China's success in pursuing its new paradigm for rapid industrial scale-up has been its ability to provide large-scale financing. Even as US innovators, including at the manufacturing institutes, develop new production technologies, the adoption rate will be both traditional and slow without scale-up financing. New mechanisms for industrial scale-up financing are needed, such as from a new industrial financing bank, from expanded authority for the DOE's loan program, or from expanding the authority of the existing Export-Import Bank of the US to scale-up lending.

Federal procurement programs, particularly at the DOD, could promote and back use of advanced manufacturing technologies in products that the federal government orders. Other steps include mapping and then filling supply chain gaps for critical technologies, improving workforce education for advanced manufacturing skills, and creating a White House office to oversee and coordinate manufacturing across federal agencies.

These represent structural system changes, but there are also lessons for improved production processes.

LESSONS FROM TESLA AND SPACEX

Elon Musk is often driven by manic and destructive behavior, and under his control, Twitter (now known as X) has increasingly been a cesspool of hate speech and disinformation.[95] But he is also the only one of the current crop of technology company billionaires to tackle hardtech manufacturing in the US. The missions of his leading

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companies aren't modest: Tesla's is to lead a shift to a low-carbon economy through electric vehicles, while that of SpaceX is to lead the way to interplanetary travel. These missions mandate innovation, and therefore innovative manufacturing, because they require reaching new production efficiencies to make their goals affordable.

The companies have evolved some important features for a new manufacturing model, challenging many prior manufacturing assumptions.[96] Deep integration of design, engineering, and production is mandatory, and all three must be linked on the factory floor, with the roles fully integrated. Design must be driven by production realities, while production must enhance breakthrough design. Every element of the production process must face intense evaluation and be redesigned and reorganized to reduce cost and improve efficiency. Outside of the laws of physics, all assumptions and assumed requirements should be discarded and rethought. Great risks should be taken in design and engineering and then systematically tested to enable product breakthroughs. Every material and component should be intensively evaluated and all alternatives considered to help drive down costs and drive production and performance efficiency. There are limits to automation; optimal efficiency can be gained from striking the right balance between people and automation.

The results indicate the success of these approaches. SpaceX built the first privately developed liquid rocket to put a commercial satellite in orbit. It was the first company to successfully launch, orbit, and recover a spacecraft, and the first to send a spacecraft to the International Space Station. Currently, it is making the largest spacecraft ever built to support a mission to Mars. SpaceX is dramatically more cost efficient than its legacy firm competitors. As for Tesla, it has driven every major car maker in the world to adopt electric vehicles.

The success of these firms is embedded in their new manufacturing process models. Such process improvements need to be incorporated as part of a new production paradigm.

IMPLICATIONS

The manufacturing problem is now widely acknowledged. In a sense, manufacturing even had its "Sputnik moment": the 2016 presidential election and the working-class backlash that it illuminated. Advanced manufacturing policies hang in the balance.

The Trump administration never fully embraced the manufacturing institutes or adopted related manufacturing innovation policies, and the same has persisted in President Joe Biden's succeeding administration, despite its spending on industrial policy approaches. Meanwhile, a few mainstream economists outside of government have accepted these ideas and advocated a rethink of the labor market or trade aspects of these issues. This expanded view, though, is by no means pervasive.

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Neither of the two major US political parties seems to understand the basics of the growth economics that lie behind this new innovation focus on manufacturing. How did the parties miss growth economics? The economist John Maynard Keynes famously gave us the simple answer when he wrote, "Practical men, who believe themselves to be quite exempt from any intellectual influence, are usually the slaves of some defunct economist." It's how he ended his 1936 magnum opus, *The General Theory*.[97]

Our political parties appear to have locked in long ago on prewar economics. The politics of each is organized around one of the two dominant factors that prewar economics thought was responsible for growth: Republicans on capital supply, with its leaders returning again and again to the popular political well of lowering marginal tax rates; and Democrats on labor supply—improving education, health, and income in labor markets. Both matter. But Solow demonstrated decades ago that technological innovation is the dominant factor in growth, and this book has argued that a strong production sector is key to implementing these gains.

The American political class has almost entirely missed the critical role of technological innovation and its power to spur innovation-driven growth. Advanced manufacturing is now a key asset in such innovation.

The economic historian Benjamin Friedman's 2005 book, *The Moral Consequences of Economic Growth,* showed that periods of higher economic growth tend to be accompanied historically by more tolerance, optimism, and egalitarian perspectives; declining economic growth periods are typically characterized by pessimism, nostalgia, xenophobia, and violence.[98] While the American upper-middle class is thriving and fine, much of the remainder of the population has been less than fine; the US population appears split along Friedman's two lines. Manufacturing productivity growth and related investment have been at low levels despite their demonstrated role in driving growth. Unless growth agendas that feature advanced manufacturing are supported adequately and consistently, we are in for a difficult time ahead. We have seen a wave of social externalities accompanying the economic decline affecting the American working class. Both economists and the political system that they influence need to get with the manufacturing program.

THE BIG LESSONS

What are the big lessons for science and technology policy from this exploration of the US manufacturing sector? First, manufacturing is part of the innovation system and must be factored into the analysis of the strengths and gaps in particular sectors. This means that a governmental role in innovation must consider the steps beyond the research stage, which takes us well beyond Vannevar Bush's linear pipeline view.

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Second, new manufacturing processes are highly creative and evolve in steps that combine new technology development and organizational and process development, joined with new business models. This was the case with the development of interchangeable machine-made parts and then mass production in the US, with quality manufacturing in Japan, and more recently with rapid production scale-up capability in China. Because complex, high-value goods dominate world trade, wealthy nations require proficiency in these manufacturing paradigms. Introduction of these paradigms spurs productivity growth, which creates real gains in the economy, which can be distributed across a population.

Third, there is an economic dimension to science and technology policymaking, which falls into the field of political economy. Mainstream American economists, while supporting a governmental role in research based on a market failure theory, understated the consequences of free trade policy for manufactured goods and opposed a governmental role in innovation beyond the R&D stage. Thus, an influential block in policymaking has opposed seeing manufacturing as part of the innovation process.

Fourth, for nations that have been at the cutting edge of this integration of innovation and production, there are consequences for failing to maintain their advantage. The US suffered significant social disruption when it missed the quality manufacturing paradigm introduced by Japan. This proved so significant that it amounted to missing an innovation wave, with the US losing technology leadership of the auto and consumer electronics sectors—creating the Midwest Rust Belt. In recent years, China's adoption of innovations in production that enabled it to scale up manufacturing rapidly further disrupted the American working class, contributing to a thinning-out of the nation's middle class and corresponding political confrontations.

Finally, engineers and scientists tell us that a host of new technologies are developing that can be the basis for a new kind of manufacturing paradigm, combining digital production, additive manufacturing, robotics, advanced materials, biofabrication, and other technologies into new ways to undertake manufacturing. What is called "advanced manufacturing" is a new paradigm that potentially offers the US an opportunity to apply its still-strong R&D system to innovation in production and improve its position in production leadership. Process improvements also must be incorporated as part of this paradigm.

DIRECT INNOVATION FACTOR 4: PRODUCTION AND DISSEMINATION

These four lessons lead to a larger one. The biggest lesson from these increasingly understood realities about manufacturing is that it is central to innovation. While, as noted

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previously, the US has thought of R&D as the essence of innovation, in fact the follow-on stages are crucial elements. Production is how we learn about the complexities of introducing innovations.

You can't understand a technology until you make it, because the production process teaches how a technology must be rethought, redesigned, and reformed to meet the demands of successful market entry. Dissemination of a produced good, in turn, teaches how to develop a technology at scale; if it is widespread, it then becomes a building block for the incremental advances that build on it, as well as the breakthroughs beyond those. If innovation is viewed narrowly as the prototype, then R&D will suffice and the first three direct innovation factors listed in earlier chapters will be enough. However, if innovation is viewed, as it must be, as the implementation at scale of a new technology, then production and dissemination become crucial. These two closely tied elements amount to our fourth direct innovation factor.

The US saw the opportunity in the 2012–2014 period to pull together the technology strands listed previously for advanced manufacturing and exploit them, to recover its capabilities for this fourth direct innovation factor. It created new institutions—advanced manufacturing institutes—to undertake this project. These adopt the concepts of innovation organization explored earlier in the book and bring together the critical actors required—industry, government, and universities—to pursue the challenge. Mechanisms to finance the scale-up of new manufacturing technologies and processes that may emerge from the institutes will still be needed, as will other steps noted in this book.

To date, the effort required to create a new manufacturing paradigm in the US has not risen to the level of the need. It remains modest compared to that of key competitor nations. The next question is whether that will change. Inventing the future is not enough; we need to make it.

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10 EXAMINING ENERGY TECHNOLOGY DEVELOPMENT

Energy transitions take a long time. Shifting from wood to coal took the entire nineteenth century. Railroads had a symbiotic relation with coal and played an important role in the transition. Railroads themselves switched from wood to coal for their locomotives and needed iron for their rails and railcars, which required coal to make and which the railroads transported.

To do so, railroads connected iron plants (and later steel plants) to the mines. When the railroads wanted to transport more, they needed more customers, so they worked systematically to encourage households and commercial buildings to shift from wood to coal. As they transported more coal, the price came down, which allowed more households to switch—but those households needed iron stoves, furnaces, and other devices.[1]

By the end of the nineteenth century, coal was king: more American households burned coal than wood by the 1880s, for example.[2] It took the entire twentieth century to bring on four other energy contenders: oil, natural gas, nuclear, and renewables.

Today, the primary fuel sources for buildings, transportation, and industry in the US are oil, which has a 36 percent share; natural gas, a 32 percent share; renewables, a 12 percent share; and nuclear power, an 8 percent share. Coal's share dropped to 11 percent by 2021.[3]

The climate imperative requires the energy transition process to speed up in the twenty-first century. The 2016 Paris accord, agreed to by 196 nations, called for reducing greenhouse gas emissions by the year 2050 to 80 percent below 2005 levels, which is needed to keep global warming to below 2 degrees and preferably below 1.5 degrees Celsius.[4] A renewed energy innovation system is mandatory.

In 2004, Stephen Pacala and Robert Socolow famously portrayed the basic approach that we have since followed for energy technology developments to tackle carbon

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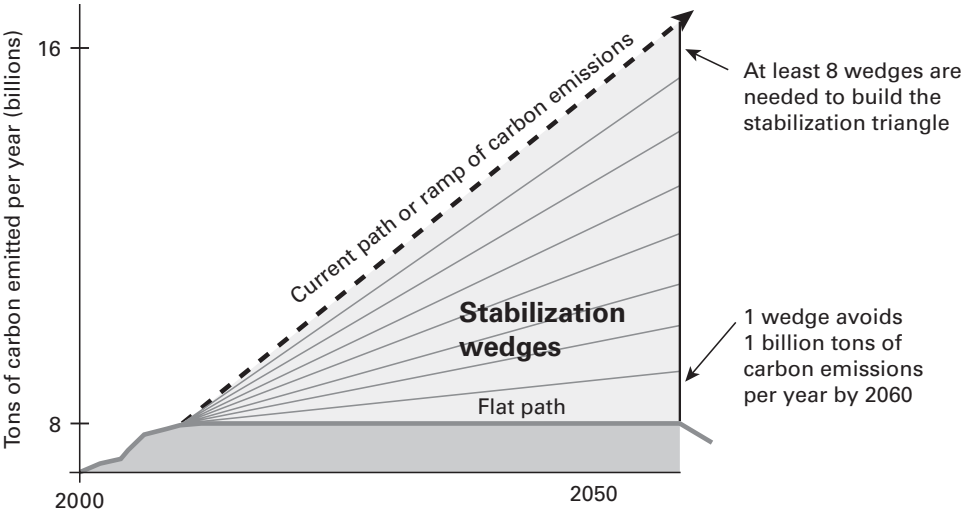
Tons of carbon emitted per year (billions)
16
8
2000
2050
Current path or ramp of carbon emissions
Stabilization wedges
Flat path
At least 8 wedges are needed to build the stabilization triangle
1 wedge avoids 1 billion tons of carbon emissions per year by 2060

FIGURE 10.1
Pacala and Socolow's stabilization wedges.
Source: Carbon Mitigation Initiative (2020).

emissions as the "wedges" theory.[5] Noting that no single silver bullet would solve the energy challenge, they described instead a mix of new technologies and conservation practices that would be needed—some fifteen major energy initiatives that they called "wedges." They explained that any seven of them, if fully implemented, could bring emissions down during the next fifty years to an acceptable level, which they estimated as avoiding about a third of the total carbon dioxide (CO_2) emissions that would otherwise be released. Each initiative could start small but would scale up over time to have the necessary impact as the century moved along.

Wedges were key both to explain the multifaceted approach required and to portray it—as can be seen in Pacala and Socolow's chart (figure 10.1).

Some of these wedges were clearly within the range of adoption and timely scale-up. Others, such as significantly reduced deforestation, a 50 percent reduction in driving by 2 billion vehicles, or widespread world adoption of agricultural conservation practices, would require major changes in both policy and human behavior that are very difficult to implement, both politically and socially, and could take quite a long time. Still others, such as technology for carbon capture and sequestration at electric utility plants, will take many more years of development and demonstration before they are ready for widespread deployment.

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In the course of their article, Pacala and Socolow argued that while additional research might well be useful, we already have the technology needed to meet the 2050 climate targets:

> We agree that fundamental research is vital to develop the revolutionary mitigation strategies needed in the second half of this century and beyond. But it is important not to become beguiled by the possibility of revolutionary technology. Humanity can solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do.[6]

This statement entered an ongoing debate between environmental and industry advocates. Industry had been arguing against a carbon tax or major regulatory measures. We're not technologically ready for the shift, industry claimed, so give us a decade or two to do the technology development required. Environmentalists supporting such legislation responded, backed by Pacala and Socolow's article, that while additional research and development (R&D) might be useful, the technology to meet climate goals already existed.[7]

This led to an unfortunate political problem, though: why fund R&D and the development of new technology if the technology and related policies already exist, just waiting to be implemented? Neither environmentalists nor industry were addressing the need for technology advances, and they settled into a brawl about what could or could not be done quickly. There was a gap in political focus on technology advancement. Of course, Socolow and Pacala were not trying to win a political debate with an argument that energy R&D should be defunded. Their point was that we should begin to meet the challenge by using our available technological capabilities, not that R&D should stagnate. But the impasse fed a delay on technology initiatives.

Two realities subsequently developed. First, advances in climate science led to an understanding that the greenhouse gas cuts required were much greater than those that Socolow and Pacala anticipated in their 2004 article to stabilize at 2005 levels. This meant technological progress was required well beyond what Socolow and Pacala and others had anticipated. Second, political progress in the US halted in 2009, when the US Congress failed to legislate a carbon cap-and-trade system (a form of carbon tax) to mitigate climate change. But even if an overall economic approach to climate was stalled, at least progress could be made on the important technological advances still required.

The two developments created a new imperative. The political logjam and the finding from climate science that deeper mitigation was required accentuated the need for technological progress.

How can we best organize the innovation system to meet that need? Wedges remained the paradigm, but technological progress became paramount.

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ENERGY INNOVATION—UNDERLYING ISSUES

Energy innovation requires getting inside the "black box" of this complex legacy system. Far more than in other sectors, the government is already deeply involved in energy, playing a major regulatory role in many sectors at the federal and state level, providing subsidies to fossil fuels and renewables alike and underwriting significant R&D efforts. The two major political parties align themselves with different technologies: Republicans tend to back nuclear power and fossil fuel subsidies, while Democrats tend to support renewables. There is some overlap in support for some new technologies, although climate remains a deep political divide. Overall, though, both parties tend to lack coherent and consistent technology policies.

Many of the new and evolving energy technologies are either not technologically or economically ready for implementation. Solar and wind technologies have made significant progress, reaching a 12 percent overall energy use share, although significant technology advances are needed to improve the efficiency and cost of both, along with much faster implementation progress. After two decades of debate, pressure from Tesla's capture of market share for electric vehicles (EVs) finally pushed other carmakers to decide that the future was in EVs and start making the investments required for the large shift. But the level of EV production is far behind what's needed: there are 276 million registered vehicles in the US, but only 2.32 million electric plug-ins have been sold since 2010.[8] Since the typical life of passenger cars and light trucks is over twelve years, this transition will be a long one.[9]

The challenge when it comes to energy is *scale*.[10] The central issue with new energy technology is scaling it up to a level that makes a difference. Without massive implementation, promising new technologies can have only a limited effect.

A public strategy around energy technology must consider scale and several other core issues. A governmental role must be very large in *scale and scope*, resembling the scale of the *Apollo* project—not like small-scale, incremental R&D programs—but with a quite different form and organization than *Apollo*, and *led by the private sector*, with *public-private partnerships* as the prevalent mechanism. The government can't simply contract to get to an energy transformation the way it did to get to the Moon.

The effort will unfold over several decades, so it will need to be *technology neutral* and avoid the lock-in of suboptimal technologies. It will need to be organized differently from the current patterns of subsidies to specific technologies, an approach that is difficult to alter and tends to create a situation of "no lobbyist left behind."

Finally, it will need to be *organized around overcoming obstacles to market launch*—not as a traditional R&D project, but focused on *implementation*.

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A NEW UNIFIED APPROACH TO INNOVATION IS REQUIRED

Tackling the massive energy challenge will require the *unified approach* to innovation spelled out in chapter 7, combining the pipeline, extended pipeline, induced innovation, manufacturing-led, and innovation organization models.

The *pipeline model*, in which R&D nurtures science advances that lead to breakthrough technologies, is relevant and will need to be strengthened because the reduction in fossil fuel emissions must be 80 percent or more. The Socolow and Pacala assumption that the needed technologies are already at hand must now be seen as overstated; we will need to go deeper, and some breakthroughs likely will be required given the problems inherent in shifting human behavior to adjust to climate demands.

We will also need the incremental advances of industry-led *induced innovation*, where a market opportunity is identified and met with innovation. Market inducements through regulations such as mandates, technology standards, or a carbon tax could be the demand push factor for induced innovation.

The *extended pipeline model*, which involves federal support that extends later down the pipeline, will also be important. The US Department of Energy (DOE) already has some of these capabilities, including a loan office to finance technology scale-up, but to tackle climate change, it will need more such authority. *Manufacturing-led* innovation, including processes and technologies as well as accompanying business models, will also be required to raise productivity and lower costs to get to the levels of technology change required to resolve climate threats. All these combine in the *unified approach,* which builds on *innovation organization*—and that is how we'll achieve what's necessary.

THE PROBLEM OF SCALING UP ENERGY INVESTMENT

In addition to the unified approach just described, there must be a commensurate level of investment. Today, less than 2 percent of the federal budget across all departments supports energy innovation. Let's examine energy R&D spending, one element of the overall innovation effort that will be required to implement new technologies.

DOE spending on energy R&D of all types is still well below what it was in 1978,[11] when—at the time of the Organization of Petroleum-Exporting Countries (OPEC) oil supply crisis—the federal government invested more than $10.5 billion (in 2020 dollars) in energy research, development, and demonstration (RD&D). If federal investment had kept pace with growth in the economy, DOE's RD&D budget would have been more than $32 billion in 2020. Instead, it was only $8 billion—about 21 percent of the department's

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budget. While 2022 legislation that will be outlined in chapter 12 has begun to change these numbers, implementation of those laws remains a challenge.

The US private-sector energy R&D investment story has paralleled the government story. After rising to a high point in the early 1980s, it fell to below half that level by 2005.[12] Worldwide, private-sector energy R&D data for key sectors shows a similar pattern, with a gradual recovery since then,[13] but is investment at adequate levels? What do leading companies in US sectors that are innovating spend on R&D?

The energy researchers Gregory Nemet and Daniel Kammen found that the biotech industry spends 39 percent of its annual revenue on R&D, the pharmaceutical sector spends 18 percent, and the semiconductor sector spends 16 percent.[14] Among established industries, the electronics sector invests 8 percent of sales on R&D and the auto industry invests 3.3 percent. Overall, private-sector investment in R&D across all sectors was 2.6 percent of annual revenue. In comparison, private-energy sector firms spent less than 1 percent.

Could the federal government offset the limited energy R&D in private-sector energy companies? What does the federal government spend when it wants to advance a major technology area? Looking at both R&D and technology implementation (in 2002 dollars), the *Apollo* program required $185 billion over nine years, the defense buildup during the administrations of Jimmy Carter and Ronald Reagan required $445 billion over twelve years, and doubling the National Institutes of Health (NIH) over five years between 1998 and 2003 required $138 billion. The ballistic missile defense program required $145 billion (in actual dollars) over its first six years. Federal energy technology development support has not been close to these numbers, although 2022 legislation could start to turn things around. Of course, these are examples of the needed size of a federal energy effort, not the way that such a program would be organized; in energy, because the technologies need to land in the private sector, a program must be led by private-sector entities.

At issue isn't just the level of R&D investment; there must be sustained and continuing investment as well. Overall, federal energy technology investments have tended to parallel the price of crude oil, with investments going up when oil prices rise and going down as prices recede and concerns fade.[15] Because technology development tends to require sustained and ongoing investment, it is difficult to organize a sustained energy program when the funding pattern resembles a roller coaster. And this underinvestment in energy technology—below what's needed to meet climate changes—and erratic patterns of support are phenomena shared across the developed world.[16]

Again, the energy challenge is a problem of scale—including the scale of R&D and implementation funding. Back in 2008, an ambitious International Energy Agency study

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evaluated technologies and consumption in energy sector after sector, estimating that reducing emissions by 2050 to below 50 percent of 2005 levels would require total worldwide investment of $45 trillion, or $1.1 trillion per year, in both R&D and technology implementation.[17] Even if widely off, the estimate still pointed to the magnitude needed.

A 2022 report by the International Renewable Energy Agency (IRENA) argues that the worldwide investment required to limit warming to an increase of 1.5 degree Celsius—a more ambitious goal—would be far greater: $5.7 trillion a year through 2030[18]—far more than the 2022 Bloomberg estimate that total global investment in low-carbon energy totaled only $755 billion.[19]

Government support for energy R&D is an important indicator in all this because it can be longer term and higher risk than private-sector R&D. Yet developed countries in 2021 invested only $23 billion research, development, and demonstration, in energy efficiency, renewables, and other new energy technologies.[20] While 2022 US legislation may help in this country, we are simply nowhere near on track to meet the midcentury goals.

LEGACY-SECTOR RESISTANCE

The previous section reads as though the climate problem could be solved if we just threw money at it. Not so. The problem is much more complex. Energy is a complex, established legacy economic sector, as discussed in chapter 7, which greatly complicates a technology transition.

The US tends to be good at the "next big thing." If Americans don't like their current technological neighborhoods, they tend to pack their new technologies into a metaphorical covered wagon and go west over the mountains to open new technological territory. As argued in chapter 7, they are used to standing up technologies in open fields, such as computing. Unlike energy, though, there was nothing quite like computing before it came along, and it was able to build up without opposition from incumbent technologies. In other words, there was no legacy-sector challenge at the beginning.

New US innovations like to land in unoccupied territory, but energy is occupied territory full of incumbent technologies organized around fossil fuels that have already gone through generations of improvement (think internal combustion, gasoline-powered vehicles, and natural gas turbines) and have become cost efficient. In other words, they have already pushed down the development cost curve.

New energy technologies have yet to do that. New technologies will face competition the moment they try to settle into the occupied territory of a legacy sector and will likely be shot at. The legacy-sector challenge is why the US is not very good at taking technologies in the other direction, back over the mountains to technologically settled territory.

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We don't tend to go west to east, so to speak. We launch biotechnology, but we have terrible difficulty trying to bring innovation into the existing and established healthcare delivery system. Technological innovation, though, is the key driver of economic growth; bringing new technologies into established sectors can mean major gains. After all, as discussed in chapter 7, more than 80 percent of the current US economy is in established, legacy sectors. Still, though, we limit our growth zone—our area for technological innovation—to new sectors, a much smaller part of the economy.

The existing energy technologies are heavily subsidized and politically powerful. New entrant technologies are up against an established "technological-economic-political-social paradigm."[21] They face established technologies that have driven down the cost curve and are economically efficient and often subsidized, backed by political supported and nurtured by social support, including education and training systems and societal assumptions about low energy costs. Against these, new energy technologies must compete on price on the day that they are introduced. That's typically difficult for new technologies that take time to drive down the coast curve with its incremental improvements and production efficiencies. The legacy competitor technologies also typically don't have to pay for their environmental and geopolitical costs (the externalities).

A carbon charge (a carbon tax or cap-and-trade system) sets a price on CO_2 emissions that aims to capture these externalities. It sends a price signal to users, raising the price of carbon-inefficient technologies so that new carbon-efficient technologies can complete at the outset and begin to drive down the price curve. A carbon charge works only if it is sustained over time and high enough to offset the costs of new entrant technologies.

There is no doubt that an economywide market pricing has advantages over other approaches in terms of overall economic efficiencies. But it is politically unlikely any time in the near future in the US, given the country's political divides. In the interim, there is an opportunity to continue to promote new technologies and to apply a mix of federal and state incentives to promote its introduction.

STEPS FOR MARKET LAUNCH

Carbon charge or not, what are key steps that need to be considered in the implementation of new energy technologies?[22] Because energy is a legacy sector, as noted previously, a unified approach to the models for the dynamics of innovation will be required. Then what? Energy technology is the ideal case study for the steps for legacy economic sectors outlined in chapter 7. Launching new technologies into a legacy sector requires, in essence, a four-step process: first, determine the launch pathways that need to be

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identified, with technologies grouped together depending on their launch characteristics (e.g., launching batteries for storage at utility scale will be different from launching batteries for EVs); second, tie policy packages to the particular launch pathways, with policies bundled across comparable technologies but organized to be as technology neutral as possible; third, identify gaps in the particular energy innovation system; and finally, fill those gaps with organizational innovations.

What do those steps look like in a specific energy technology context? For the first step, concerning *technology launch categories*, we can identify a number of paths:

• There will be *experimental technologies* that simply require an extended period for R&D, such as fusion or hydrogen fuel cells.

• There are *potentially disruptive innovations that can be introduced and start to scale in niche markets*. Light-emitting diode (LED) lighting is one example; because of its long life, this technology filled niche applications that incandescent and florescent technologies could not, so it was possible to introduce LEDs into these markets and drive down the cost curve over time to make the technology affordable in broader applications. Solar photovoltaics initially filled similar off-grid niche needs.

• Then are *secondary innovations that face an uncontested launch*. These are components in larger systems that face immediate market competition based on price but are acceptable to the system manufacturer. These would include batteries for hybrid vehicles or EVs, which are components in larger vehicles, or enhanced geothermal energy, which could be incorporated into a larger utility system. In both cases, the system owner, car maker, or utility can accept them provided they are price competitive.

• Another category includes *secondary innovations that face contested launch*. These are components in larger system with inherent cost disadvantages or that face political or nonmarket economic efforts to block their introduction. Carbon capture and sequestration technology, for example, adds major additional costs and a significant efficiency reduction to a fossil fuel plant, so a utility won't just accept them—it will have to be required to do so. Other examples include new nuclear power plants and offshore wind farms that have faced significant political opposition, limiting their introduction.

The next step is to *tie policy packages to the particular launch category*. Here, there are multiple elements:

• First, virtually all energy technologies, regardless of launch category, need help with *front-end support*, which could include R&D, prototyping, testing, demonstration, public-private R&D partnerships, monetary prizes for the best technologies, and support for education and training.

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• Second, many technologies will need *back-end incentives* (carrots). While technologies that can be introduced into a niche market may not need them, secondary component technologies that can't yet compete with established technologies on price may well need these carrots. Back-end incentives include tax credits for new energy products, loan guarantees, price guarantees, government procurement programs where the government buys the product, and new product buy-down programs. Solar, wind, and EV technology have all been beneficiaries of such programs.

• A third element comprises *back-end regulatory mandates* (sticks) for secondary/component technologies that face a contested launch and corresponding political battle over acceptance. These include standards for particular energy technologies in building, construction, and appliances; renewable portfolio standards (that require regulated utilities to rely on a set portion of renewables for electricity generation); and fuel economy standards for vehicles. While incentives—the carrots—are often politically acceptable, imposing regulatory sticks is typically difficult politically because they increase costs. For example, utilities thus far have been able to resist regulations that would require the adoption of carbon capture and sequestration at fossil fuel plants.

The next two steps are connected: *identify system gaps* and then *fill those gaps*. The gaps can exist on the front end of the innovation pipeline, as well as at the back end, and can occur at every stage, from R&D to prototype, demonstration, test bed, and deployment.

The Advanced Research Projects Agency–Energy (ARPA-E) provides an example. The DOE had a basic research capability through its Office of Science, as well as late-stage applied programs through its Energy Efficiency and Renewable Energy (EERE) Office. But there was a gap between basic and applied programs. ARPA-E, which received initial funding in 2009, was designed to apply a Defense Advanced Research Projects Agency (DARPA) model to the gap, identify breakthrough technologies that could resolve a major energy technology challenge, and reach back to the R&D needed to develop that technology.

Other system gaps could include the need for a wholly owned government corporation for back-end efforts, such as sharing the financing of demonstration projects, speeding the scale-up of energy technologies, or financing the installation of efficiency and related new technologies in residential or commercial building markets. Filling such a gap, for instance, could involve creating a think tank to develop a detailed road map for particular energy-related innovation and to recommend optimal policies in support. Efforts to develop energy technology standards and support test beds for new technology evaluations could also be in order to fill gaps in the present system. While the DOE has a loan office, its authority could be expanded for scaling up new technologies.

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To accelerate the introduction of new energy technologies, we need to get inside the black box of how innovation in the sector actually occurs. The framework that we have described is aimed at enabling that effort. The challenge, though, is complicated by the problem of new functionality.

When the desktop computer arrived at scale in the 1990s, it offered the ability to perform new functions, from computer games to spreadsheets, that previously had not been possible. Early personal computer (PC) consumers were happy to pay a premium for PCs because they offered new functionality and let us do new things—even though they pale in comparison to today's computers in speed, power, and capability. Energy, however, is more complicated. EVs are still cars, and electricity, whether generated from wind, solar, or coal, still arrives through wall outlets. The source is indistinguishable. New functionality in energy technologies may evolve, but for the time being, the first generation of new energy technologies does not offer much of it. That means that for now, consumers are reluctant to pay a price premium for new technologies; these technologies will have to compete on price from the moment they enter the marketplace. This complicates the technology implementation picture and means that governmental interventions, from support for front-end experimental technologies to back-end incentives and regulatory sticks, will be required.

Again, to get to the level of energy innovation that we require, we will need to apply all the models of innovation dynamics in a unified approach; apply the four-step framework to sort through the wedges of innovation; identify the launch pathways and create the right mix of incentive packages (both on the front and back ends); and identify the gaps in the energy innovation system and fill them. Energy technologies are not the most complex technology challenge the nation has faced, but energy does represent the most complex technology *implementation* task we have faced.

CONFRONTING THE POLITICAL FAILURE OF CAP AND TRADE WITH ALTERNATIVE APPROACHES

Thirty years ago, American policymakers settled on a price on carbon as the chosen way to head off the oncoming dilemma of climate change.[23] The concept came from the dominant economic doctrine, neoclassical economics.[24] The doctrine is organized around the concept of maximizing allocation efficiency, with pricing signals—from interest rates, currency supply, monetary policy, taxes, and pricing mechanisms—as the preferred tools. Given this centrality of allocation efficiency, markets are central, and market distortions and interventions are to be avoided. Admittedly, however, market distortions are pervasive, and much of neoclassical theory deals with correcting market

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failures through such means as providing public goods, offsetting externalities, upholding information transparency, promoting competition, and encouraging new entrants despite economies of scale.

Neoclassical economics has used these constructs of market failure and offsetting externalities to pursue climate policy. Although the field of behavioral economics has made incursions into neoclassical economics,[25] the assumption remains that economic actors, at heart, pursue their rational self-interests. This means that their economic activities can be measured, and the field can thus be measurement-based.

Carbon prices—including the pricing approach initially proposed in the US of capping total carbon emissions and allowing trading for a declining base of emissions permits (known colloquially as "cap and trade")—can fit within this construct. But if a factor *cannot* be measured and analyzed within a manageable number of variables, it is exogenous to neoclassical economics outside the measurable box, and so outside the system. Complex social systems, for example, fall outside its reach. As discussed in chapter 1, neoclassical economics has had great difficulty addressing innovation systems, which are—of course—highly complex, with multitudes of actors and therefore variables that are not widely understood or necessarily measurable.

Cap and trade, because it fits squarely within the neoclassical constructs of allocative efficiency, market failure, and offsetting externalities, was a solution to climate change embedded in neoclassical economics. By contrast, innovation-oriented policies for climate, because of their variables that are often impossible to measure, were never well understood in the neoclassical context.

The neoclassical toolkit did make some major contributions to environmental progress in the US beginning in the latter part of the twentieth century. Most notably, the acid rain provisions of the Clean Air Act Amendments of 1990 introduced a cap-and-trade system that efficiently controlled sulfur dioxide emissions from power plants.[26] In addition, a trading system for chlorofluorocarbons, established under the Montreal Protocol, aimed to control ozone layer depletion and nitrogen oxides through trading to limit smog on the US East Coast.[27]

These trading systems helped emitters find and adopt flexible, low-cost compliance strategies; they also encouraged prompt deployment of technological solutions. The needed technology innovations, though, were readily at hand. As discussed previously, progress on climate change requires dramatic innovation advances in energy. While there has been significant progress on some areas, such as solar, wind, and EVs, more is needed to improve efficiencies. And there are many potentially critical technologies—including carbon capture and sequestration, utility scale storage, next-generation nuclear,

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hydrogen, and fusion—where significant additional advances are needed before they will be ready for deployment at scale.

Transforming a major world economic sector fundamental to basic human needs, equivalent to at least 10 percent of the world economy, with at least $15 trillion in embedded infrastructure and investment, demanding numerous but complementary technology pathways, and to be implemented over a multidecade period is a daunting task. The US has succeeded in remarkable single-thrust technology projects achievable within a decade—the Apollo and Manhattan projects are touchstones—but has never systematically organized for anything as complex as an energy technology transformation.

For years, the neoclassical economic focus on allocation efficiency has been running into an innovation brick wall for climate, precisely because the technological solutions are not readily at hand, as they were with earlier environmental problems such as acid rain. This technology challenge meant that many industries faced carbon pricing proposals with great uncertainty over what their technology options might be for compliance to avoid major pricing penalties, which hardened and expanded their political resistance.

Ultimately, the US political system in 2010 rejected a price on carbon through a cap-and-trade scheme imposed economywide.[28] The political balance on the issue in the US has only deteriorated since then. This is why it is so important to look more systematically at *innovation policy* in the context of the climate technology challenge.

The climate crisis has exposed the ideological lines between neoclassical economics policy and innovation policy. US policymakers continue to assume, as they have for decades, that putting a price on carbon is the strategy for addressing climate change. It is remarkable that they have never assembled a systematic back-up plan. Innovation policy is that alternative and, as discussed previously, we are beginning to see the required conceptual framework, organized around reducing barriers to market launch.

Progress has been made on innovation policy approaches since Congress rejected cap and trade. The DOE, the lead federal agency for energy innovation efforts, has added capabilities and mechanisms to further technology advances. At the front end of the US energy innovation system, new R&D institutions have been formed within DOE to better translate research into actual technology advance. They include the following:

• The *Energy Frontier Research Centers* program provides $2 million to $4 million in funding annually to centers that are competitively selected at universities and laboratories to work on basic research problems, tied to breakthrough advances in energy technologies.[29] More than forty centers operate in thirty-four states, searching for new energy opportunities in the basic research space.

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• *Energy Innovation Hubs* work to push emerging energy advances at a larger scale—in advanced nuclear reactors, artificial photosynthesis, battery storage, critical materials, and water innovation—toward commercialization.[30] Reflecting their scaling role, the hubs each receive around $20 million in annual funding.

• The *Advanced Research Projects Agency-Energy* (ARPA-E), discussed in chapters 4 and 6 and later in this chapter, receives about $400 million a year in funding and is modeled on DARPA.[31] It seeks particular innovations and then looks for revolutionary breakthroughs to get to implementation. It is working in what it calls the "white space" of technology opportunities—higher-risk projects that could be transformational but have seen little previous work.

• *The SunShot Initiative* was initially established in 2011 to make solar energy cost-competitive with fossil fuels by 2020.[32] Situated in DOE's EERE Office, its R&D efforts were funded in its first years at $70 million to $100 million annually. In 2017, DOE announced that the initiative had successfully helped meet the utility-scale solar cost of $0.06 per kilowatt hour three years earlier than expected, and a new goal was set to achieve utility-scale solar at $0.03 per kilowatt hour by 2030—which would make it among the least-expensive options for new power generation and lower than the cost of most fossil fuel–powered generators.

• The *Clean Energy Manufacturing Initiative* and its *Advanced Manufacturing Office* formed in 2013 in EERE have aimed at applied technology advances to drive down production costs for new energy technologies, make them competitive, and improve overall industrial efficiency.[33] The program sponsors R&D and applied work and has set up a network of nine advanced manufacturing institutes—industry-university collaborations as test beds in such areas as power electronics, advanced composites, and smart manufacturing. These institutes receive approximately $70 million over five years to advance manufacturing technologies. (In 2022, the program was split into two offices, one focused on industrial efficiency and the other on advanced manufacturing technologies.)

• The *Office of Technology Transitions* was formed as the central hub for enabling improved transfer of technology innovation for commercialization from DOE's extensive R&D programs, including its network of federal laboratories.[34]

On the back end of the US energy innovation system, scaffolding support is needed to bring new technologies toward implementation and deployment. The programs and incentives include the following:

• *Tax and other incentives* for new energy technologies.[35]

• *DOE financing* for energy technologies through loan guarantees.[36]

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• *Government procurement*, particularly through the US Department of Defense (DOD) when its missions require energy advances.[37]

• *Federal regulatory authority* for reduced emissions and energy consumption from power plants,[38] automobiles and trucks,[39] and appliances.[40] Regulations can help drive (as well as curtail) new innovations.

• *State-level regulatory authority and incentives*. States and regions in the US can amount to nation-sized economies, and some have been leaders in pressing for new energy technologies, particularly California[41] and the US Northeast. Thirty-eight states, for example, have renewable portfolio standards requiring power producers to provide a set minimum share of their electricity from renewable resources.[42]

None of these programs is operating at the scale of investment and support required for an energy transformation, and both the front and back ends of the innovation system remain subject to the ups and downs of the political process. But there is a framework that can be further developed. New elements have recently been added in 2022 legislation that is summarized in chapter 12.

Cap and trade is strong on "demand pull" but short on "technology push." It's likely that both will be needed, but they do not have to operate in parallel; progress on the latter may be a requirement for implementation of the former because it is an enabler. An amalgam of policies in the US that could comprise a backup plan on climate has been gradually emerging. The plan includes technology push mechanisms that have been strengthened in the past decade, with a focus on both the front and the back ends of the innovation system. The approach relies for its needed demand pull on current regulatory tools and incentives that are less economically efficient than cap and trade but will allow for interim progress.

In addition, more innovation system elements will need to evolve; for example, there is a significant gap in the system for scale-up financing for production of new energy technologies. This evolving innovation system may prove more palatable politically because it applies a series of more manageable policy bricks that can be put in place by many actors, unlike the economywide, single economic construct of cap and trade.

ARPA-E AS AN ENERGY INNOVATION MODEL

Of the programs enumerated here, ARPA-E is perhaps the most interesting and deserves elaboration.[43] Information on ARPA-E's establishment and an explanation of how it works can be found in chapters 4 and 6; the elaboration here focuses on its specific role in the context of what has been discussed earlier in this chapter.

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ARPA-E, authorized in 2007 and funded in 2009, was intended to bring a DARPA model to fill a gap in the energy innovation space for breakthrough R&D not covered by other parts of DOE. It follows the basic DARPA model, but with some important variations. ARPA-E must spur technologies in a legacy sector, whereas many of DARPA's advances, including in computing, can be put out in open, frontier sectors. DARPA operates within DOD's extended pipeline model and can hand off its technologies to the massive procurement programs of the military service branches; DOE has no procurement budget, and thus no direct way to scale up energy technology projects. The venture capital (VC) sector had largely pulled out of energy technology development as too high risk by the time that ARPA-E was funded, so to find a way to scale up technologies, the agency had to get creative.

TECHNOLOGY IMPLEMENTATION

It is in technology implementation that ARPA-E's organizational innovations have been particularly interesting. It established a Tech-to-Market team to work on commercialization of each of ARPA-E's technology projects, with members experienced in VC, start-ups, and defense contracting. A member of this team is assigned to work with the ARPA-E project director and each research group to plan commercialization approaches. DARPA liked this idea so much that it copied it, creating its own Tech-to-Market team and hiring away ARPA-E's Tech-to-Market director—the ultimate compliment to ARPA-E.

ARPA-E *examines the technology implementation process* before making any R&D award. There must be a plausible, workable pathway to commercialization for each proposed project, and the pathway is revisited periodically as research progresses. ARPA-E has also built ties to the applied agencies within DOE, particularly EERE, so its projects can get access to follow-on funding from within the department—what ARPA-E calls "in-reach" funding. Even absent outside support, this allows ARPA-E's technology projects to move toward application.

ARPA-E typically funds a portfolio of projects in a technology thrust area, such as improved batteries for transportation. Researchers from universities and smaller companies with different technology approaches are typically part of the portfolio. These researchers typically don't want to share their technologies, but ARPA-E project directors bring them together to *share ideas for common learning* and progress. Putting industry and university thinkers together has been an effective way to accelerate progress.

The scarcity of funding and highly competitive selection process *creates a "halo effect"* for many ARPA-E award winners. A technology funded by ARPA-E garners prestige that tends to command an immediate interest in what is left of the outside VC and technology financing fields.

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ARPA-E also helps its researchers understand and *connect to industry's "Stage Gate" process*. While ARPA-E pursues a technology visioning process, established industry R&D projects go through an intense and periodic weeding-out process that evaluates risk and potential return at fixed stages. Understanding and fitting into this industry process can be key to advancing a technology.

SHARPENING RESEARCH VISION, SELECTION, AND SUPPORT

Given its limited resources, ARPA-E wants to avoid replicating work that is already underway. It goes through a process to identify the "*white space" of technology opportunities*, seeking breakthrough areas where work is simply not yet being done. A *two-stage selection process* for reviewing projects allows rejected projects to respond to criticisms and be reconsidered, which sharpens the process at each review stage.

ARPA-E has developed an *empowered project director culture*. Project managers meet as a group, with the director, to decide on technology fields to pursue and decide which research to fund. This collaborative, idea-sharing approach tends to sharpen decisions. Project managers also are expected to have what the agency calls "religion" about their own projects—that is, an eagerness to push their technologies to implementation.

Like DARPA, ARPA-E emphasizes *hands-on relations with awardees*. The grant selection process is only a beginning. The agency's project directors help awardees with nurturing ideas from others working in the relevant field, solving research challenges as they arise, making connections with companies, and transitioning their technologies. Project directors become in-person coaches closely involved with their awardees.

A *technology fellows program* at ARPA-E places outstanding recent graduate students with project directors. They bring the latest ideas fresh from academic research to the agency, helping further sharpen the quality of thinking. The mentoring dynamic and cross-generation contact foster collaboration and support quality thinking from the project directors. DARPA has copied the program.[44]

SUPPORT COMMUNITY

Building a support community has been vital for ARPA-E. It furthers the research mission, enhancing the pool for collaboration and ideas, but it also provides much-needed political support.

Early on, ARPA-E began to hold an *annual summit* to showcase its awardee's projects and help make connections for the new energy advances that the agency nurtures. It rapidly became the most important yearly event for new US energy technologies, attracting VC companies, energy start-ups, established companies, political leaders, and DOE officials.

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POLITICAL DESIGN

Different than policy design (the usual sole focus), *political design* is a key for programs and institutions that support R&D. Federal technology investment doesn't drive itself; it is deeply integrated into the political process. The right political design helps an agency become politically sustainable over time, thus aiding the sustainability of *policies*—so long as the political design complements policy and supports quality policy design.

ARPA-E has been an example of getting this combination right. Its approaches to building a support community set out here have helped ensure a supportive political constituency that is oriented toward backing program quality because it seeks optimal technology advances.

How has ARPA-E performed? As of spring 2022, its projects, funded with approximately $3.5 billion over thirteen years, have attracted more than $10.3 billion in private-sector follow-on funding and $21.6 billion in exit valuations from twenty-five mergers, acquisitions, and initial public offerings from firms receiving ARPA-E support. Some 131 ARPA-E project teams have formed new companies to advance their technologies, 288 licenses have been issued for ARPA-E sponsored technologies, and 270 ARPA-E projects have partnered with other government agencies for further follow-on development.[45] The projects have generated 896 US patents.[46]

This is not to say that ARPA-E doesn't face challenges. Technology implementation is particularly difficult in the energy legacy sector. Overall, however, the ARPA-E organizational lessons discussed here make clear that it's not enough simply to fill innovation system gaps with new mechanisms. It is vital that new innovation organizations also innovate dynamically in their approaches. It's not just about gap-fillers; it's about *innovative* gap-fillers. ARPA-E provides an instructive example.

SCALING UP ENERGY TECHNOLOGY START-UPS

The US relies on entrepreneurial firms to bring innovation into its system. Energy, because it is a legacy sector in which the large, incumbent firms are committed to a fossil fuel technology paradigm, relies in particular on new firms to introduce an alternative low-emissions paradigm. An International Energy Agency study has found that more than half the reductions in CO_2 emissions required to meet climate goals will have to come from technologies that are only in early stages as of today,[47] which makes bringing new firms into being a key priority.

For much of the 2000s, beginning in 2004, the US had a "clean tech" boom; investment in new energy firms multiplied some ninefold, led by VC firms. The clean tech boom led investors to place $25 billion into start-ups from 2006 to 2011, but then they

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lost more than half their investment because by 2009, the boom was turning into a bust[48] that drove VCs away from new energy technologies for many years. More than 90 percent of the companies founded after 2007 failed to return the capital invested.

What happened? A global recession dried up the market for follow-on investment. Massive Chinese dumping of low-cost solar panels blocked thin-film and other more advanced solar technologies in the US. The biofuels sector was undercut by lower oil prices and the rise of fracking for natural gas. And in 2009, the US Senate failed to pass a climate cap-and-trade bill.

These external developments, though, weren't the root issue. An MIT Energy Initiative study found that the deeper problem was that the VC industry was counting on the same kinds of returns in three to five years that it could obtain in software.[49] But clean tech energy firms required too much capital to demonstrate, build, and scale up their technologies. The energy development time frame was ten to fifteen years, not three to five.

Storage start-ups, biofuels firms and advanced solar companies had technologies that weren't mature enough to displace established, legacy industries and were too expensive for VCs to commercialize. Company founders, although expert in their technologies, lacked experience in manufacturing and business operations.[50] Founders of IT companies, in contrast, often *did* have these skills, and they also had the advantage that their products were creating new markets, not trying to land in a legacy sector to compete with existing products.

Fast forward to the 2020s, and clean technologies are much more reliable and far less expensive. Wind and solar can compete directly with coal and natural gas plants on price following a major buildout of solar and wind farms and the scale-up of production. They are becoming trillion-dollar sectors. Major price reductions and improved performance in lithium ion (Li-ion) batteries are making EVs competitive, and the world's automakers, seeing continuing improvements ahead, are now in the process of shifting their production lines over to EVs. These developments have significantly reduced the risk of renewables and EVs as major markets materialize. This means that the investment in these sectors is lower for incremental advances and scale-ups. There has been a corresponding increase in the number of VC firms backing clean tech, both generalist firms and firms organized around energy climate challenges.[51] Clean-tech venture investment levels in a broad swath of technology categories have grown since 2017,[52] although an inflationary spiral in 2022 negatively affected this growth.[53]

The underlying challenges noted here for VC investment in clean tech—risk, cost, and time—remain. VCs still distrust hardtech areas such as energy technology; the risk of boom and bust remains. And VC is not ready for the massive scale-up of energy technologies

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required. All told, US venture investment raised $128 billion in 2021 for all purposes—software, biotech, services, hardtech, and others—compared to the $1.2 trillion size of the US energy sector that year.[54] There are, however, alternative models that could supplement and be more sustainable and patient than VC, as discussed next.

INNOVATION ORCHARDS

In 2015, Rafael Reif, then the president of the Massachusetts Institute of Technology (MIT), noted that while biotech and software firms coming out of his institution were receiving venture funding and scaling up into successful companies, ideas that took more than five years to mature were not. He had seen the rapid prototyping firms that had cropped up in Shenzen, China, and realized there was no equivalent system for this stage in the US. "Our highly optimized, venture-capital driven innovation system," he noted, "is simply not structured to support complex, slower-growing concepts that could end up being hugely significant—the kind that might lead to disruptive solutions to existential challenges in sustainable energy, water and food security and health."[55]

Reif's solution to this major problem in scale-up for new firms with these kinds of ideas was something called "innovation orchards." VC firms were essentially funding the equipment, technology, and know-how that new firms needed to thrive. Were there other institutions—new innovation orchards—that could create technology and equipment-rich space for start-ups, give them access to deep know-how about both technology and company creation, and start them off with a regional support system for their innovations? If scale-up for a new energy technology was typically ten years, could that period—boosted by a period in an innovation orchard institution—be cut to five and get a technology into range for a handoff to VC, private equity, or other financing?

The orchard model is not what traditional start-up incubators do—early-stage business planning and idea prototyping—but it is all about the scale-up stages. Reif saw this new kind of innovation space as assisting new firms that had big ideas about prototyping for design, demonstration, testing, and all the way to pilot production; it could move the start-up down the scale-up curve. The new space could allow start-ups to reduce the risk of their technologies.

"To tackle our biggest societal challenges," he concluded, "we need an innovation pipeline that delivers every drop." True to his idea, Reif in 2017 created an orchard at MIT called The Engine.[56]

THE ENGINE

Research universities have all the innovation orchard prerequisites: lots of equipment, technology, and know-how. Could they add an additional purpose to their existing

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early-stage research and become scale-up centers? The Engine was MIT's answer, becoming a kind of postdoctoral program for innovative hardtech start-ups.

In its first five years, The Engine housed around three dozen start-ups in a range of technologies that were scale-up ready—that is, past the early planning stages and ready for advanced prototyping, demonstration, testing, and pilot production. They got space, access to equipment, and know-how for approximately two years, and continuing contact and support when they "graduated." Reif also raised an initial $150 million that was made available as bridge funding to help the start-ups in the scale-up process, organized as a VC fund for participating firms; The Engine raised a second $230 million VC fund in 2020.[57] In 2022, The Engine acquired 155,000 square feet of renovated space at MIT to support more than 100 companies with 1,000 employees, to be used for labs, offices and maker spaces, and fabrication facilities.[58] It stands as a scale-up model for other universities to consider.

CYCLOTRON ROAD AT LAWRENCE BERKELEY LAB

Funded through DOE's Advanced Manufacturing Office, Cyclotron Road was founded by ARPA-E veterans who were seeing the difficulty that start-up firms supported by ARPA-E were having in the scale-up stage. Located at DOE's Lawrence Berkeley National Laboratory, above the campus of the University of California Berkeley, it was named for the road that goes to the lab where the physicist Ernest Lawrence's famous 1946 cyclotron was located.

Cyclotron Road recruits entrepreneurial scientists and engineers that have energy technology advances with potential societal impact around which they want to form companies to bring them to market. It draws on the lab's technology, equipment, know-how, and facilities to support these efforts. The entrepreneur teams involved in Cyclotron Road projects receive salaries from DOE programs as fellows for two years. They aim to enable the fellows to identify the optimal path to market for their technology, exploring at a broad spectrum of commercialization models. Many of the teams look beyond traditional VC and align with strategic investors, angel investors, large corporations, or sometimes philanthropic efforts.[59]

In effect, the Cyclotron Road approach is to park a scientific motorcycle gang inside advanced labs and let them use the equipment and loot the place of ideas as they try to scale up their companies. The competition for fellowships is stiff, with Cyclotron Road applying ARPA-E-like criteria to the selection of teams and their projects.

DOE has long had difficulty moving advances made in its national labs out into the marketplace. This is not surprising: ideas move with people, and the labs are attractive places for scientists to work with good pay, job security, and advanced facilities. Few

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have wanted to take the risk of leaving to start a company. Cyclotron Road is an alternative way for the lab to undertake technology transfer—an outside-in approach that brings entrepreneurs into the lab, as opposed to the traditional inside-out approach of the labs transitioning their own ideas. It may be a more effective model. A 2018 impact study of the first four cohorts of teams found that close to 80 percent made a market or technology pivot with their ideas; all found funding for their prototype development, and 70 percent completed their initial prototype.[60]

The Cyclotron Road model has since been picked up at two other major DOE national labs, Argonne and Oak Ridge, which are running comparable programs. Some of the leaders from Cyclotron Road have formed a new organization, Activate, in an effort to spread the model in the form of support for technology-oriented fellows at host universities and laboratories.[61]

TECHBRIDGE

TechBridge, an arm of the Boston Fraunhofer Institute, supports energy start-ups. Its role is in the prototype, testing, pilot production, and technology validation spaces. Rather than identify start-ups and then support their scale-up, TechBridge works the other way around. It first identifies area companies that want to tackle an energy innovation problem and then links them to area energy start-ups with which they could partner.

Established companies have little interest in partnering on technologies that will disrupt their business models or that they are already pursuing through their own R&D efforts. But often, they are interested in partnering on technologies that are complementary to their business models that that they aren't researching themselves. TechBridge has positioned itself to help both sides in arranging these partnerships. It knows the company community well from its Fraunhofer Institute role, and it also has strong ties to area energy start-ups, knowing which ones might fit as a partner with an established firm. It can play an honest broker role in an atmosphere where the established company typically is skeptical of the start-up and its technology, and the start-up typically is worried that the established company will steal its ideas.

TechBridge is also experienced in forming the agreements that protect both sides around technologies that both want to pursue. Since VC is hard for new hardtech firms to obtain, these company partnerships can be a critical alternative avenue for a start-up to scale its technology.

Working with its Fraunhofer parent, TechBridge also can play a key role in technology validation for both industry and start-up partners. When the two partners have worked together to create a prototype, they can take it to the Fraunhofer, which has a long history of providing technology evaluations for its industry participants. The Fraunhofer

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lab does a full review, evaluating the strength and durability of the proposed product, its manufacturability, and its likely cost of manufacturing at various scales, and then makes recommendations for improvements. Assuming that the response is positive, the start-up is thrilled because the famous Fraunhofer Institute lab has validated its technology as workable, helping ensure follow-on support. And the established firm is delighted, too, because the start-up, which it probably thought was a little crazy, has come up with a working innovation that Fraunhofer says can be practical.

This technology validation role by a respected, independent third party can provide a major boost to a technology—it is a little like what approval from the US Food and Drug Administration (FDA) does for biopharma products. Outside the life sciences, though, the US has never developed a mechanism for this potentially important scale-up step. The TechBridge/Fraunhofer example points the way.

GREENTOWN LABS/MASSMEP

A joint project conducted by Greentown Labs and the Massachusetts Manufacturing Extension Partnership (MassMEP) offers a fourth example of an innovation orchard. Greentown Labs is a Boston-area incubator for energy technology start-ups, and MassMEP is a state- and federally supported organization that advises small and midsize manufacturers on new processes and technologies. Greentown and MassMEP teamed up for a year to work with technology-based, innovative start-ups that emerged largely from university research benches.[62]

The energy start-ups at Greentown Labs know their research well but typically have no idea about how to manufacture products. On the other hand, the small manufacturing firms that belong to MassMEP know the manufacturing process intimately but don't undertake technology-based R&D. The partnership began with a successful one-year experiment in 2014 to get start-ups and small manufacturers past this innovation gap. First, both Greentown and MassMEP surveyed their members to gauge interest, which turned out to be substantial on both sides. Next, MassMEP staff experts in production held office hours at Greentown to get the interested start-ups oriented on planning their production needs. To educate the start-ups about manufacturing processes, Greentown Labs also hosted workshops and "lunch and learns," open to start-ups, which brought manufacturers to Greentown for half-day informational panels—after which start-ups were able to speak one-on-one with manufacturing representatives and begin to build relationships.

Manufacturers said that they were interested in the program because they didn't do their own R&D and wanted access to other business models and to show their employees some of the intensity around start-ups; they also saw the important role that

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entrepreneurship was playing in the Boston-area economy and wanted to help it. Start-ups were interested in participating because they wanted access to practical manufacturing knowledge and potential partners who could help them get into production. Many found that doing design prototyping with a nearby area manufacturing company, where they could hang out and brainstorm together on short notice, was a major spur to significant improvements to their designs. In other words, proximity spurred innovation. Further, before they got the opportunity to work with MassMEP manufacturers, many start-ups thought that they had to work with prototypers in Shenzen to scale up, running the risk of transferring their ideas and designs.

Greentown's involvement formally ended after the first connection was made; the process of negotiating and signing a contract was left entirely to the manufacturer and the start-up, and with no subsidies going to either side, both had to risk their own funds. But Greentown and MassMEP staff continued to provide mentorship and advice to both start-ups and manufacturers as they progressed in their relationships. In all, thirty-two start-ups were interested in receiving assistance from the program, and eighty-three manufacturers were interested in working with start-ups. The program facilitated some 140 connections between start-ups and manufacturers and resulted in nineteen signed contracts. The Greentown-MassMEP model is an important one for how to get hardtech start-ups into the production stage by linking them to an area's small manufacturers.

These varying approaches to creating an innovation orchard are each dynamic in their own ways. They are not just a possible alternative to the limited availability of VC for hardtech areas such as energy. They also present new kinds of opportunities for doing a better job of scaling up start-ups into successful technology-based companies.

An advantage of each of these four approaches is that they are relatively inexpensive. They simply repurpose existing institutions—research universities, federal labs, a manufacturing institute, an incubator, or an alliance of small manufacturing firms—that have already invested in equipment, technology, and know-how and give them an added purpose (namely, assisting start-ups to scale). It doesn't involve major capital expenditures in facilities, equipment, and space because these investments have already been made at the host institutions.

THE PROBLEMS OF DOMINANT DESIGN, TECHNOLOGY LOCK-IN, AND STRANDED INNOVATIONS

Energy provides a good illustration not only of the challenges of technology scale-up but also of ways that an initial technology, once established, can become a barrier to subsequent improved technologies.[63]

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There is a recurring pattern in the evolution of technology in which a particular technology approach often becomes a "dominant design."[64] This design, in turn, tends to lock in users, who uniformly adopt it—which can end up driving out existing alternative technologies that could perform the same function, or keeping out newer technologies.

Technology lock-in can be beneficial because it accelerates process innovation and drives down costs for the dominant design, which in turn expands its adoption. It also creates a major risk, however—namely, that promising innovations with the potential to outperform the dominant design over time may be cut off. This leads to "stranded innovations," promising alternative technological advances that get isolated from resources and are unable to evolve and reach markets, never getting the chance to mature fully and compete.

Energy storage is a good example. It is widely understood that the current electric power sector requires transformation, and emissions from the power sector need to drop to near zero if we are to meet climate change goals. Providing storage for the energy grid could be a key enabler for this transformation, making the grid faster, cheaper, and more efficient. Renewable energy—solar and wind—needs to assume a much larger portion of power production compared to fossil sources, but these sources are variable, of course. The sun doesn't shine at night and is affected by clouds and seasons, and winds shift.

Storage could offset that variability, making power from renewables more stable and reliable. There are a range of storage technologies that fit into four basic categories: mechanical (pumped hydropower, compressed air storage, and flywheels); electrochemical (nickel-based batteries, lithium ion (Li-ion) batteries, flow batteries, and liquid metal batteries); chemical (hydrogen); and thermal (passive and active thermal storage).[65] Although pumped hydro has dominated the limited storage grid sector in the past, there are geographic limits to where it can be applied.

In recent years, Li-ion batteries have moved to the forefront of these technologies. Li-ion batteries were introduced into the consumer electronics sector in 1991 and became the dominant technology there, driving down production costs for these batteries. They then shifted over to dominate hybrid vehicles and EVs, where additional improvements were made and costs were driven down further. Now, there is an effort underway for Li-ion batteries to dominate the grid storage sector. Grid-scale storage is still an emerging field, but by the end of 2017, Li-ion batteries had captured global market share exceeding 90 percent compared to the other nonpumped hydro technologies.[66]

Sounds positive, right? The cost of Li-ion batteries is coming down and improvements are continuing. They are helping us make progress on storage, a critical need of the energy system. But then we need to confront the details. There are three ways to compare the technologies: energy and power, reliability and durability, and cost efficiency and

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value generation. Li-ion, although it continues to evolve, is not necessarily optimal from these perspectives.[67]

Concerning durability and reliability, Li-ion batteries have been prone to overheating and are limited in their durability, cycle life, extent of discharge, and charging time. Long-duration storage—storage for not just an hour, but for a day or even weeks—is a big challenge for Li-ion. Their storage-capacity costs will likely remain too high for many years for them to be adopted widely for long-duration use on the grid.[68]

There are also supply chain concerns. Cobalt is a key component and must be sourced from unstable nations. China now dominates Li-ion battery production and is moving to use this dominance to dominate EV production, so there is a geopolitical set of problems too. The costs and limits on the availability of key materials used in Li-ion batteries create a price level that is problematic for grid storage.[69]

As Li-ion moves to lock in on grid storage as it has in electronics and transport, there may be alternative technologies that offer advantages, but they are just beginning to undertake the development process and may become stranded innovations. For instance, vanadium redox flow batteries could be competitive with Li-ion and last far longer. Liquid metal batteries may prove significantly less expensive, safer, and more reliable. Passive thermal storage could cut the demand for energy in heating and cooling systems, and active thermal storage systems could provide long-duration, dispatchable power resources.[70] If Li-ion locks in, we may never find out how these technologies could compete in the three critical areas cited here.

There is a *virtuous* cycle that has helped Li-ion emerge in electronics and transport.[71] As users gained confidence in the dominant design's quality and performance, and workers were trained to use it, network effects emerged, where a rise in use increased the value and utility of the new technology to each user. Policymakers have contributed significantly to Li-ion's transport dominance by providing major government support and incentives. As innovation accelerates and prices decline in this phase of the technology life cycle, there is typically a shakeout of producers: process innovation typically means rapid increases in the scale of production, which squeeze out less competitive and financially weaker producers. These steps have contributed to the rise of Li-ion. Users conclude that when a dominant design is superior in price, performance, and potential, there is little to be gained from pursuing alternatives.

The virtuous cycle for Li-ion that has helped it dominate transport and may enable it to control grid storage means that there may be a parallel vicious cycle for the alternative technologies for grid storage.[72] The young companies that build the alternatives are undercapitalized, buyers have difficulty financing projects that use them, and public policymakers neglect them. Even when these firms gain a foothold in the market, they have

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difficulty scaling up production due to the high capital requirements and long lead times required. The shift of production to the lowest-cost locations undermines innovation investment in countries such as the US, which are more research-intensive compared to production-intensive nations such as China.[73]

Of course, there are policy options that can keep potential technology competitors that offer advantages in the game. The federal government can support R&D in these alternative areas. State and local governments can encourage regulatory approaches to support storage that require applying a mix of technologies by their utilities. Regional storage consortia could be implemented to help make connections between technology firms and utilities. Regulatory rules can be shifted to allow storage technologies to compete better with generation technologies. But the purpose of this discussion is not to list policy fixes; rather, it's to put on the table a deep challenge for energy innovation technologies as the nation and the world confront climate change.

Climate is at least a four-decade challenge. It is not like the much more straightforward nine-year challenge of getting to the Moon or the Manhattan Project's four-year challenge. Because the technology challenge for climate will be lasting and require multiple generations of technologies, we must consider the problem of dominant design of new energy technologies, the accompanying problem of technology lock-in, and the resulting problem of stranded innovations. We will need policy steps to avoid these three dilemmas so they don't become major roadblocks to continuing technology advancement.

AN OVERALL PERSPECTIVE

This chapter has explored many pieces of the overall energy technology puzzle. What do they look like when they are all snapped together?

The energy technology challenge is driven by the need to confront climate change. The *wedges* theory provided a snapshot of how to confront this new reality: there was not going to be a single technology fix, but instead a range of technologies and accompanying policies were required, each of which could gradually scale up and become a wedge to reduce emissions over time. The energy technology task became creating a series of wedges. Because energy is such a massive world economic sector and enabler for many other sectors, though, it was never going to be easy.

An energy technology strategy must simultaneously be *very large in scale*; *led by the private sector*, because that's where its technologies need to land; *technology neutral* to avoid locking in less-than-optimal technologies; and *organized around launching the new technologies* into markets. That's why developing a new unified innovation approach that merges the *pipeline model*, industry-led *induced innovation*, the *extended pipeline* model,

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and *manufacturing-led innovation*, all operating in coordination, is a major task of *innovation organization*.

Energy technology in large part presents the *problem of scale*, and transforming energy technologies is not simply a matter of throwing money at the problem. A new approach to innovation organization is imperative for this complex, established *legacy sector* where fossil fuel technologies sit within a fortified castle surrounded by a protective moat in the form of a *technological-economic- political-social paradigm*. Technology implementation will require *identifying the launch pathways* for different energy technologies; *identifying supporting policies* that include both front-end RD&D support and back-end and regulatory mandates; *examining the gaps* in the system; and *filling the gaps* by putting into place the required organizational and policy mechanisms.

All of this challenges the neoclassical economics model that has dictated that a technology shift would be driven by market pricing, which so far has proved politically difficult. This market pricing focus, in turn, has caused us to neglect a coherent technology strategy. We now need one.

As for the new institutional mechanisms needed, ARPA-E provides a good example (but not the only one) aimed at formulating the energy technology breakthroughs that will be needed on the right side of the pipeline and working on the left side of the pipeline on the science and engineering (S&E) advances to get there. Beyond new institutions, we need new ways to take on the complex s*cale-up of technologies* are also required. Risky energy technologies don't fit well with the short-term approach of VC; new organizations that focus on assembling the equipment, technology, and know-how needed to nurture start-ups through scale-up (like those described earlier), are crucial. Once new technologies are derisked, more traditional capital sources become more accessible.

Finally, we must recognize that climate is a multidecade problem that will require multiple generations of technologies. The pattern of technology advance often leads to dominant technologies that tend to lock in. That can strand new technologies that are better suited to the challenges but can't assemble the resources required for scaling once another lock-in has occurred. Policies need to be designed to prevent these potential roadblocks to energy technology progress.

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11 US WORKFORCE NEEDS AND WORKFORCE EDUCATION

There is an expanding body of literature on innovation ecosystems as being essential to technology-based growth, as noted in chapter 2. However, the role of workforce education as a factor in these systems has largely been missed by these analysts.[1] It must be included as part of the innovation equation.

In the three preceding chapters, we explored three sectors of the US economy that require serious policy attention to ensure that the nation sustains its innovation leadership. These and other sectors also need *workers* to do the jobs. Workforce needs vary significantly among economic sectors, and each sector requires its own approach to preparing a workforce for the jobs of the future. Five major sectors of the US economy—manufacturing, in-person retail, healthcare delivery, construction, and information technology (IT)—offer a snapshot of present and future needs.[2]

Let's begin with the *manufacturing* sector, where employment has stabilized at around 12 million jobs in 2023 after massive job losses between 2000 and 2010. This sector has an aging workforce. so an estimated 2 to 4 million jobs will open up in the coming decade due to retirements. With new technologies and processes for advanced manufacturing being adopted by manufacturers, higher levels of skills will increasingly be required for this workforce. That means that we need a major new workforce training system for both incumbent workers and new entrants.

In-person retail is a disrupted sector with declining jobs as online ordering has grown, but a new model may be on the way. Companies are pursuing an approach called "omnichanneling," which combines online and face-to-face entry and requires staff who have more skills with online technologies. Although much of retail cut back on workers in the last decade, the advantage of in-person retail turns out to be those very people. Successful firms are increasingly finding that it pays to keep staff in stores who have been upskilled

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to be fluent guides for customers, helping them navigate the ever-more-complex product options.

Healthcare delivery will also require new skills. Because of an aging population with growing health needs, this is an expanding sector. New medical technologies are entering healthcare and creating new professions apart from traditional nursing and medical doctors. The result is more jobs with higher skill needs, which requires new training systems—and overcoming barriers that the established health professions have erected to limit entry.

As in healthcare, the number of jobs in *construction* has been growing. Housing shortages are prevalent in many major metropolitan areas; the nation needs more than 7 million new affordable housing units for low-income families; we have a huge houseless population; and climate change–related disasters are increasingly upon us.[3] Billion-dollar disasters requiring extensive rebuilding have increased by four times in the last four decades, and buildings produce a problematic 40 percent of carbon emissions. Construction processes, though, remain traditional and slow to change in this legacy sector, which has seen declining labor productivity since 1968. International firms applying higher-tech industrial practices for modular construction could make inroads into significant parts of the US construction market, and the competitive pressure may change the nature of construction jobs. This will fuel the need for expanded workforce education to operate new systems.

Finally, there's *IT*, which continues to be a rapidly growing field in which there simply are not enough workers with the requisite skills. Already, some firms are looking at adding "no collar" workforces to meet their needs, upskilling high school–educated workers since colleges are graduating far too few workers with the needed skills. Other firms are implementing apprenticeships with intensive additional education, for example, to educate for midlevel IT and software skills.[4] All these developments point to the need for a major IT workforce education effort.

These five sectors, which together constitute close to 40 percent of total US employment, are all different—some are growing, while others are stable or declining—but what they share in common is a significant need for workers with higher levels of skills. They all point to a pressing need in the US for renewed workforce education aimed at developing a more technically skilled workforce.

The same can be said more generally for all US jobs in science, technology, engineering, and mathematics (STEM), which have grown faster than non-STEM jobs since 2010. STEM jobs in the US are good jobs: workers in STEM occupations have higher median earnings—some $30,000 higher annually—and lower unemployment than their non-STEM counterparts.[5] STEM jobs include workers with and without college degrees—STEM

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jobs can be both middle- and high-skilled.[6] Many STEM job opportunities are projected to grow in the future. But despite that good news for American society as a whole, STEM education in the US is not as strong as it needs to be to create the talent base needed for a leading innovation system. And as we know from chapter 2, the size and capability of the talent base constitute a direct innovation factor.

THE SCIENCE AND ENGINEERING TALENT BASE

Creating the science and technology talent base is akin to an assembly line, and each stage in that line needs to be strong for the system to work well. Schooling at the elementary and secondary levels (K–12) is the entry point—and students at those levels in the US, compared to the rest of the developed world, are not testing as high as needed to ensure this talent base going forward.[7] STEM education in K–12 classrooms is the foundation for later stages of science advance and sets attitudes about science, but a 2019 National Assessment of Educational Progress (NAEP) found low proficiency levels that decline as students move through the K–12 system.[8]

National Science Foundation (NSF) figures from the next stage, college, also point to the problems. There simply are not enough college students receiving degrees in the fields that we need. NSF counts degrees in the social sciences in its definition of science and engineering (S&E) degrees, and those—accounting for the largest number in its count—don't fit well with the physical, engineering, and biological science requirements of technology innovation, exacerbating the problems. International students on temporary visas account for a very large percentage of master's degrees—50 percent of engineering and 57 percent of computer science master's degrees, for example.

As for doctorates, S&E fields constituted 65 percent of those conferred by American universities in 2019. After the year 2000, S&E doctorates rose faster than the total number of doctorates awarded, with the largest percentage in engineering, computer sciences, and medical sciences. International students on temporary visas earned more than half of US doctoral degrees in computer sciences, engineering, and mathematics and statistics in 2019.[9] The figures for international students matter because these students don't necessarily stay in the US to work once they finish their degree programs—further draining the talent pool.[10]

The importance of STEM education to the US innovation economy is borne out by the sheer size of the STEM workforce: more than 36 million people—23 percent of the total US workforce—are in occupations that NSF identifies as requiring STEM knowledge and expertise, which it breaks down into three levels with varying characteristics: S&E occupations; S&E-related occupations; and middle-skill occupations; that is, positions that

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Table 11.1
NSF STEM workforce characteristics

Occupation Category	Size of Workforce (millions)	Bachelor's Degree
S&E	8.6	76%
S&E-related	13.1	60%
Middle-skill	14.3	12%

require STEM skills but typically don't require a bachelor's degree for entry, including installation, maintenance and repair positions, skilled construction trades, and skilled production jobs.[11] Table 11.1 details the size of the STEM workforce and educational attainment in these three categories.

A 2022 report from the Center for Strategic and International Studies summarizes the key barriers to and gaps in US STEM education.[12] Young adults are not pursuing STEM degrees because of the high cost of a college education and how much time is required to pursue a degree. Lack of access to adequate high school–level math and science curricula, a feature of many schools in both urban and rural areas, is another barrier; large percentages of US high schools do not offer calculus, physics, chemistry, or even Algebra II, which is a gateway class for STEM success in college. A serious shortage of qualified STEM teachers fuels this, with many teachers in science and math classes lacking specific degrees and training in the subjects that they teach.[13] These barriers at the K–12 level translate into a gap that limits future opportunities for students to obtain quality jobs in emerging industries, maintains the shortage of skilled labor.

Gaps in the S&E talent base cannot help but affect the nation's innovation capacity. A 2021 US Department of Defense (DOD) study concluded that the US is at risk of losing its competitive advantage in advanced technologies if the workforce is not equipped with the advanced skills needed to develop and field cutting-edge emerging technologies:

> Decades of neglect have left the robust system of technical schools the nation once relied upon for industrial training badly weakened and the existing workforce is rapidly aging out, taking irreplaceable tacit knowledge with them . . . Programmatic responses to education and training needs still largely focus on four-year STEM-based programs rather than digital industrial skills on the factory floor.[14]

In summary, a 2021 National Academies report titled "Call to Action for Science Education" concluded that "science education is not the national priority it needs to be, and states and local communities are not yet delivering high quality, rigorous learning

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experiences in equal measure to all students from elementary school through higher education."[15]

TALENT STRATEGIES FOR HIGHER EDUCATION

The economist Paul Romer's "prospector theory" (detailed in chapter 1) argues that the nation or region that fields the most well-trained prospectors finds the most gold. Translation: the largest, best-trained scientific and technical talent base will create the most significant technology advances. If that is the case, then what should a talent strategy at the higher-education level look like?

The federal government's current indirect approach, subsidizing private-sector demand for advanced technologies through tax incentives and the research and development (R&D) tax credit while assuming that there will be a supply response to support the needed talent base, is too indirect. More than two decades ago, Romer found that it has a limited effect.[16] We need a new incentive system aimed at the primary supply mechanism—universities. Romer argues that that's how we'll get a "steady flow of people trained in the scientific method" and "in the state of the art in their area of specialization."[17] It is the way to increase the total quantity of inputs that go into the R&D—talent, as Romer finds, being the big one.

Today, the US system of higher education—at both the undergraduate and graduate levels—is not structured to solve this problem. The details of why are less important than the overall picture, which Romer has presented as "undergraduate institutions that are a critical bottleneck in the training for scientists and engineers" and "graduate schools that produce people trained only for employment in academic institutions as a side product of producing basic research results."[18] We need these institutions not only to increase the number of graduates to work in the innovation sector, but to improve graduates' skills in applied work so they are better equipped to enter the private sector.

To break this logjam, Romer offered a number of policy fixes that have yet to be implemented years later. Among others, they include the following:

- Award training grants to universities that increase the numbers of undergraduate students receiving S&E degrees.
- Create a new type of graduate-level applied degree that is better matched to industry needs.
- Establish portable fellowships that pay for three years of this training.

As noted earlier, solving the education problem has broader benefits for US society as a whole, which until the arrival of tight post-COVID labor markets had been increasingly

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characterized by expanding wage inequality that disrupted the traditionally strong American middle class and democratic values. The Harvard economists Claudia Goldin and Lawrence Katz have shown this compellingly.[19] New technologies require ever-higher educational attainment, which means workers must be well educated to realize the gains of technology advances. In effect, there is a race between education and technology. Those who keep up with technical education accrue the gains from technology advances, while those who fall off the rising education curve miss those gains and risk income stagnation or even decline.

Goldin and Katz argue that if the nation wants to narrow income inequality and restore more widespread wage mobility, it needs to revitalize education attainment, allowing the spread of technology-based growth to go to a much broader base in the society, not just the top tiers that have college educations. Their work illustrating wage inequality underscores the societal importance of making available the education that can provide the general population with the skills to keep up with technology advances. In turn, that will allow the US to maintain its innovation lead in the world.

FIXING AMERICA'S BROKEN WORKFORCE EDUCATION SYSTEM

We also need to open the aperture and look beyond higher education to focus on the technical workforce. In 2022, 33 percent of the US population over age twenty-five had a bachelor's degree or higher, but the bulk of the population did not: 9 percent had not achieved a high school diploma; 28 percent had only a high school education; 15 percent had attended college but did not earn a degree; and 10 percent had an associate degree.[20] These numbers put workforce education at the forefront of education needs. But we need to rethink workforce education in this country because there aren't just deep problems—the US workforce education system for technical education is *broken*. Undertaking that task is critical if the nation is to continue its technological advances *and* have a workforce that can innovate and implement these innovations. We must figure out how to upgrade skills and ensure that workers get the training they need—issues posed because of the profound changes in jobs in the US.

Manufacturing, throughout most of American history, has played the leading role in productivity gains. Speaking to the need for upskilling, what is meant by a "manufacturing worker" has changed. Today's newest factories look more like clean labs than the mills of old. Data from the Bureau of Labor Statistics (BLS) reveal the evolution:[21] the number of lower-skilled production workers has been decreasing, while the number of high-skilled workers such as machinists and welders, as well as very high-skilled workers

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such as engineers and scientists, is increasing. Production-level workers now make up less than 40 percent of manufacturing jobs.

This is part of a general trend in US labor markets: required skills are moving steadily upscale. If high-skilled jobs are defined as those requiring some college education, BLS found that these jobs now include 37.7 million workers, rising from 28.7 percent of the workforce population in 2006 to 33.4 percent by 2012.[22] At the same time, the proportion of lower-skilled workers declined by 7.5 percent. Another study showed that in the period from 2007 to 2016—the Great Recession and its recovery period—jobs were filled overwhelmingly by persons with a bachelor's degree or higher, while there was a decline of 5.5 million jobs for those with high school degrees or less. Nearly all the new jobs after that recession—11.5 million out of 11.6 million—went to those with at least some postsecondary education.[23]

These overall trends continue. In other words, most of the new jobs that the twenty-first century will require skills held by only a minority of the current US workforce. Education is becoming more necessary to avoid falling behind the advancing technological curve. If work is upskilling, is there a way to provide effective training to the groups that are increasingly left behind?

Six decades ago, the economist Gary Becker argued that US labor markets generally supply suboptimal levels of skills training.[24] Little has changed. Labor market competition among firms tends to create an underinvestment in skill training because the gains from such training can't be adequately appropriated by the firm providing the training. In other words, companies aren't willing to invest in worker skills because competitor companies frequently hire away these trained employees and reap the benefits of their improved skills. Employers, then, to the extent that they provide training, have tended to build their programs around narrowly defined, firm-specific skills that will be of less value to other firms.

With deep societal challenges around quality-job creation, a general upskilling already under way, and the entry of new digital technologies, there is already a growing consensus on the need for improved workforce education. Spelling out the *specifics* of how the workforce education system is broken makes clear what we need to fix.

First, the problem of *disinvestment by government and employers* cannot be overstated. Both government and employers, until very recently, have been cutting back for many years on their investments in workforce education[25] at the very time that income inequality had been growing, workers needed to upskill, and the need for quality jobs was increasing. A 2016 economic report to the president[26] found that the number of employees who received *any* employer-sponsored training dropped 42 percent between

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1996 and 2008. In turn, corporate spending on training as a share of gross domestic product (GDP) declined from more than 0.5 percent in 2000 to 0.33 percent in 2013, although this spending has been increasing. More than 30 percent of US workers report that they have never received training of any kind. Although there is much talk and growing interest from large employers about implementing apprenticeship programs, there were only 636,000 workers in registered programs in 2021, and these historically have been dominated by one sector, construction.[27] On the government side, federal funding for workforce education programs fell 70 percent between 1979 and 2008[28] and has gone up only modestly since then.

The US government also *significantly underinvests in direct workforce training programs*, dedicating just 0.1 percent of GDP in active labor market programs compared to the member-countries of the Organization for Economic Cooperation and Development (OECD) average of 0.6 percent of GDP. Moreover, the US now invests less than half of what it did on such programs thirty years ago as a share of GDP. This means that US workers are increasingly on their own if they want to obtain the training that they need.

In the broken US system, *work and learning are profoundly disconnected*—that is, the education system is not connected to the working world. This gap creates a major barrier for students trying to find quality employment and careers. Other nations, particularly Germany, Austria, and Switzerland, use apprenticeship programs to make the connections between work and learning seamless, assuring high levels of technical skills and corresponding low youth employment, but the US has no comparable system.

Government programs have gaps and are not linked. US Department of Labor programs focus on the unemployed and underemployed, which is important, but these programs do not include the higher technical skills and incumbent workers and so don't tackle the need for upskilling the workforce. The US Department of Education has a well-funded program of student aid for poorer students (Pell Grants), but they are not available for workforce education, only for college education. In turn, the programs of the two departments are neither linked nor even complementary, exacerbating the gaps in their programs.

All of this is exacerbated by the loss of vocational education as a feature of the American landscape. In fact, *high school–level vocational education in the US has largely ended*. Vocational education had two major problems: it was too often low quality and it was used as a way to move working-class and minority students out of a college track. Rather than fix the system, education reforms initiated in the 1970s have largely shut it down. The nation said at the time that we would instead send everyone to college, and then we didn't. *Quality* vocational education (also known as *career and technical education*), however, is an important tool that needs to be part of upskilling the workforce.

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So, too, are community colleges; they are a unique American asset, positioned well to provide workforce education. But *our community colleges are underfunded*; they tend to be treated as the poor stepchildren of state higher-education programs. In addition, their *completion rates are often low*—in the 30 percent range. If this completion rate was 60 percent or more for the 4.2 million students enrolled in community colleges in 2021,[29] US workforce numbers would look a lot better.

The problems persist as we go up the education-level ladder. *Most colleges and universities don't believe that they have a role in workforce education*; they see that as something for high schools and community colleges to address. In a system with few recognized credentials, though, the college degree is king. These schools need to refocus to include career-oriented skills in their curricula. And they need stackable certificate programs that can help students make progress toward these degrees while gathering employer-recognized skills along the way.

Three more broken elements are important to mention here. One is that *lifelong learning is missing* from the equation. Skills require frequent upgrading; completing school cannot mean that one is done with education. We need colleges and universities to update their programs to offer lifelong learning opportunities—and not only for their traditional eighteen-to-twenty-five-year-old cohorts.

We also need new curricula, especially advanced technical education programs—*but they are underfunded*. Robotics companies are developing robotics curricula, but this is not developing in many other areas of advanced manufacturing. Two government agencies are supporting curriculum development in advanced fields: NSF's Advanced Technological Education (ATE) programs and the Manufacturing USA manufacturing innovation institutes, but they need more support.

Finally, the *labor market information system is broken*, which results in weak and disorganized labor markets. This must be fixed. Efficient markets require efficient information systems—markets actually are information exchange systems. US labor markets are highly decentralized and provide labor market participants only limited information when they make life-changing job decisions. Employers don't know the job skills of prospective employees, workers don't know the skills that employers want, and educators don't know what skills they should educate for. Employees who want quality careers don't know where optimal career opportunities are or what to do to prepared for these opportunities.

Federal agencies already collect extensive data on employment and income in various agencies; working in cooperation with employers and schools, this information could be pooled to form a much stronger information system. Given digital information capabilities, it should be possible to construct a sound workforce information system, but only limited efforts are underway to do so.

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Legacy sectors are hard to change, as discussed in earlier chapters. Our workforce education system is itself a legacy sector, with actors fixed in their existing routines and patterns. Change agents will be required if we are to make the fixes described here.

FILLING THE SYSTEM GAPS: THE EXAMPLE SET BY COMMUNITY COLLEGES

The growth of IT demands new skills, and the result is that more high- or middle-skilled jobs require education beyond high school. Hence, the critical credential for most high-quality jobs in the US is a college degree, and these jobs increasingly go to the college educated. The barrier here is that two-thirds of adults lack college degrees.[30]

To summarize some key points, colleges and universities control that critical credential, and yet they are not engaged in workforce education; they see that as a task for high schools and community colleges. High schools, in turn, are not well connected to the workplace. On top of that, many states shut down their vocational education beginning in the 1970s (although some have been rebuilding it or establishing solid *new* technical high schools, as well as comprehensive high schools with strong technical programs offered along with traditional academic programs). The result is that students at both the high school and college levels face a major work/learning gap. That's precisely why we needed a new system of workforce education that connects these disconnected worlds of work and learning and that includes a new credentialing system for employers, educators, and workers. This is especially needed to build a skilled technical workforce.

New approaches have begun or are needed that could form the basis for a new workforce education system for that technical workforce and fill the many gaps discussed earlier. Many community colleges, which sit at a critical juncture in American workforce education sandwiched between high school and college, are setting an example in this area. These institutions have the potential across the US to step up and play a greatly enhanced role in solving the nation's workforce education problems. Most of them already offer education in technical skills and take this role more seriously than their high school and college/university counterparts—so they can be a connector to employment and careers.

There is also an expanded role for employers. Quality workforce education is possible only with significant employer involvement. We need employers for apprenticeship and training programs, to help establish workforce education standards and certifications, and to contribute to strong community college programs.

The approaches being taken, or developed, include the following:

- Improving community college completion rates: Some community colleges have worked to turn around completion rates through programs such as merging remedial

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and technical courses, so the remedial work connects to the technical skill the student needs for a well-paying job. State tuition programs to fill the gap between Pell Grants, the federal program that funds low-income students in college programs, and actual tuition, also help.

One critical cause of the completion problem is that many students are underprepared and before entering college-level programs, they must take remedial courses that they often never get past. This has largely been solved in the network of twenty-seven Tennessee Colleges for Applied Technology (TCAT), where *all* students are prepared for college-level work in courses directly connected to their chosen career field.[31] The courses thus don't feel remedial, and there is no differentiation between remedial and nonremedial students. At the same time, students start their career technical education courses, choosing from the seventy career programs offered, so they get to see from the start the job opportunities that their program can create. The programs lead to certificates and associate degrees and also offer specialized training for skills needed by larger area employers. This approach is effective systemwide: the TCAT completion rate is 81 percent, with job placement rates into the student's field of study at 86 percent—far above most community colleges.

- The trifecta—reaching a broad range of students: Community colleges should not just be educating their own community college students; they should also have programs that reach high school students and incumbent workers.

Asnuntuck Community College in Connecticut's aerospace corridor provides a great example.[32] It has developed what it calls the "Trifecta" program, which reaches not only its own community college students, but also students from five area high schools, who come to study manufacturing skills in afternoons beginning in their junior year. It also has a major outreach program with groups of area companies, upskilling their incumbent workers.

- Short courses: It can be quite difficult for adults in the workforce with families to commit to a semester-long course; six- to twelve-week courses are much more manageable. In response, some community colleges are developing short, modular courses that can be stacked for certificates to meet particular skill needs. Since the college degree remains a key career determinant, these short courses should also lead to associate or bachelor's degrees.
- New curricula for new technology skills: At the federal level, the ATE program and the Manufacturing USA manufacturing innovation institutes can be better funded to develop the missing advanced curricula in the many emerging fields with new technologies entering the workplace.

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In Indiana, one of the strongest US manufacturing states, twenty-two Ivy Tech community college campuses have manufacturing programs with a unified curricula so employers know the skills that students from any campus will have, but also with flexibility built in to address regional employer needs.[33] Each campus has labs with manufacturing equipment, and each works with employer industry advisory boards that feed responses to faculty; these groups also meet twice a year specifically to upgrade their curricula. This advisory mechanism means that schools can emphasize certifications that the companies want. Industry also provides teams of mentors for each campus program.

- New education technologies: Workforce education faces a major problem: the existing system is simply not at the scale to meet upskilling needs. Online education—with prerecorded videos (not Zoom sessions) that use the best online teaching approaches, frequent assessments, and feedback loops—can be a key part of solving this problem.[34] While it can't substitute for in-person workforce training, it can be a strong supplement, carrying much of the content and information required for skills training and leaving the hands-on portion to the in-person element. It can cut instruction time, saving instructors for hands-on and mentoring, significantly improving efficiency. As they develop, virtual and augmented reality technologies can also assist with the hands-on component.
- Apprenticeships: Apprenticeship programs that connect students to jobs with solid career prospects break down the work/learning barrier. The best of these are programs that link technical education programs at community colleges to employers offering jobs with training and mentorship in the workplace. Youth apprenticeships beginning in the junior year of high school appear to be a particularly promising approach.

Trident Technical College in Charleston, South Carolina, the equivalent of a community college, links high schools, the college, and area companies in a program that begins in a student's junior year with morning courses in high school that emphasize science and math, technical courses in the early afternoon at the college, and part-time paid work at an area company during the school year and full-time work during summers and holidays. Students are halfway to an associate degree when they finish high school and get jobs that pay well, and their employers are often willing to fund their second year at community college. The program takes students out of what can too often be a disruptive high school environment and moves them to the much more mature settings: at community colleges, where the average student is twenty-nine and students are already in the workforce; and at companies where typical workers are at least in their thirties and committed to pursuing their careers.

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Such apprenticeships can lead students directly into solid jobs and careers that can also fund further higher education. "Apprenticeship Light," a less-intensive internship program that includes both work and education, is another approach.

- Employer partnerships with community colleges: Beyond the apprenticeships mentioned earlier, some community colleges are working closely in partnerships with employers to create new workforce education opportunities. For instance, Asnuntuck Community College sends faculty to large and small factories to teach courses for incumbent workers in a range of advanced manufacturing skills to upgrade their skills. Lorrain County Community College in northeast Ohio[35] has built an alliance with the Ohio Association of Manufacturers to build curricula in advanced manufacturing skills and helps lead Ohio Tech Net, a clearinghouse that joins Ohio's other independent community colleges and the manufacturers association to circulate new manufacturing curriculum. It offers stackable certificates for programs in manufacturing skills that can lead to two-year degrees. It builds industry certifications into its academic programs, so students can also gain recognized industry credentials. Through its "learn and earn" program, Lorain has students working with employers as they earn Lorain credits, and it connects to high schools in a program that creates pathways to from high school to technical programs at the college.

  There is more to the employer role, too, as discussed later in this chapter.

- Unified agency efforts at the state level: While federal Labor and Education Department programs are disconnected, states can connect these programs to deliver more unified approaches at the state level, linking state education, workforce, and economic development programs. Massachusetts, for example, formed a "skills cabinet": agency heads meet bimonthly to develop workforce programs jointly across the state education, labor, and economic development departments. No agency can make workforce education plans without the concurrence and involvement of the other two.[36] This step has led to a major regional workforce planning effort that enables community college efforts to be integrated with the common plans and programs across the agencies.

THE UNIVERSITY ROLE

Community colleges are increasingly stepping up to help solve the national workforce education problem. But what about universities, which are key as the "owners" of the critical credential—the college degree—that has become the differentiator for economic well-being?[37]

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Unfortunately, as noted, they have thus far largely failed to embrace their potential role in workforce education. But if the US is to build a new workforce education system, and recognizing that one-size education will not fit all (hence the importance of community colleges), four-year colleges and universities need to play a larger role.[38] In some cases, we will need a mix of these actors.

For example, *developing education content for higher-end technical and engineering skills* will likely best fit universities, although technician-level content development will likely be shared with community colleges and industry. The actual delivery of technician content will fall more to community colleges, while higher-end technical skills will be a four-year college or university role. However, colleges and universities can play an organizing and supporting role with industry and community colleges, which could help with technician-level content and delivery. And in new technology areas, such as advanced manufacturing and machine learning, the lines between technician and engineering content overlap and university-developed content may be particularly needed. Like community colleges, colleges and universities need to increasingly be offering certificates to supplement their degree programs and scale up to meet growing needs, in part through online materials.

Whereas community colleges that offer online courses generally lack the resources to develop them or ensure that they optimize learning science in their delivery, colleges and universities are already deeply involved in *developing online offerings*. Leading platforms offer thousands of online courses from hundreds of universities, with hundreds of millions of students enrolled.[39] Many are relevant to community college students, and more development could be targeted there. These may require a university development lead, but they will also need to be tied to community colleges and industry for workforce education.

Organizing a *delivery framework across institutions and skill areas* could be a university responsibility. In the ATE program, for example, program funds go predominantly to community colleges, but universities often assist with coordination, curriculum design, and online offerings. Researching and testing optimal teaching models and applying lessons from learning science, particularly as online education grows and creates blended learning opportunities, should also be a university task. Figure 11.1 illustrates this range of potential college and university roles.

Colleges and universities also need to improve their own performance in graduating college-level students who are genuinely prepared for sound career paths. This means they need to do the following:

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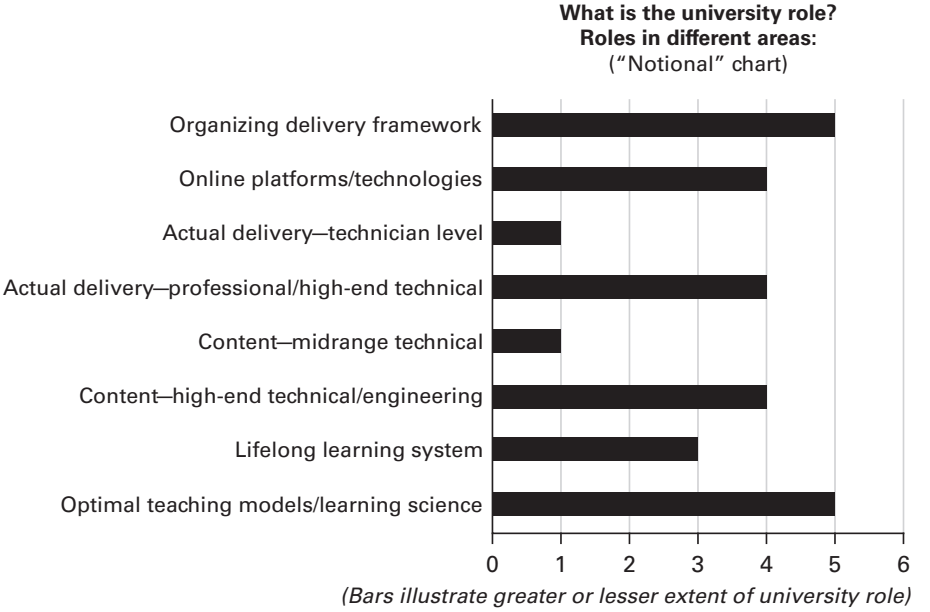

FIGURE 11.1
University role in workforce education.
Source: Bonvillian and Sarma, *Workforce Education*, 129.

• *Develop better data for students* about education, skill supply, and demand projections, business expansion, and overall workforce quality and needs, so students can see where career opportunities connected to their education lie.

• Align education programs to *match identified labor market demands*, following from these data. That doesn't mean scrapping the classics—colleges need to continue to educate people. But they need to do a better job at offering education options for students based on fields with career opportunities.

• Significantly improve *counseling about career pathways*, taking a more sophisticated approach than holding job fairs to serve out-of-town employers and, instead, supporting students in their education and career decisions and helping to identify those who need additional assistance.

Shifting job content suggests that a college degree acquired in the beginning of a career cannot answer the need for the continuous acquisition of new skills over the course of a career. With ongoing technical change in the workplace, *lifelong learning* will

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increasingly be required. Organizing this into a system could also be largely a university task, but with *more varied delivery mechanisms*.

A great deal of attention will be required on developing *alternative credentialing programs*, including certificates, badges, and competency-based programs, which can also stack toward degrees. *Adaptive learning* approaches will also be needed, including assessments for prior learning and allowing students to learn on their own pathways that meet their career needs while acquiring needed competencies. Again, colleges and universities, working with industry, states, and community colleges, could play a key development role in both of these areas.

THE ROLE OF EMPLOYERS

Employers need to play a central role in workforce education well beyond what has been described above in this chapter. The message to employers is that it's not someone else's problem. They can't leave it to schools and governments to fix; whatever programs we adopt as a nation must incorporate industry leadership.

For instance, we must have a better school-to-work transition—and who controls work? Employers do.

For employers to fulfill their necessary role will require a new level of engagement; the problem is bigger than company human resource departments. Many employers are experiencing shortages in skilled workers, and the COVID pandemic may have accelerated an ongoing demographics shift, where the next generation will be smaller *and* not educated in the needed skills.

To tackle these problems, employers will need to work together. Single-company workforce education solutions tend not to last, typically ending once a company shortage is filled or there's an economic downturn that leads to workforce cutbacks. Programs shared across companies tend to be more enduring. Collaborative programs survive better during economic downturns. Building shared solutions also tends to reduce the perennial problem of raiding by one firm of another's trained employees. Plus, because firms working together on workforce education are able to pool resources, that can be the key to whether small companies can participate.

A three-way alliance between employers, schools, and state and local governments is critical for workforce education success. Programs at the community colleges discussed here all feature strong employer involvement. This is also behind the successes noted earlier with paid internships and apprenticeships that are breaking down the work/learning barrier in some parts of the country. This would not happen without employer collaboration with strong programs at community colleges, high schools, and colleges.

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The workforce education system also needs employers to play a central role in setting standards for education that reflect actual job requirements.

Employers don't need to act alone. Again, as some are already doing, they can work with state and local governments and regional education institutions to make workforce programs happen.

KEY TAKEAWAYS

The US is facing a challenge in meeting its science and technology requirements: its science and workforce education for its scientific and technical talent—across the different levels and types of STEM-related jobs—isn't generating the numbers required or the skills needed for its innovation economy.

On the science education side, part of the problem is that the economic signals in our university system aren't working: the federal government's current approach is too indirect. It subsidizes private-sector demand for advanced technologies through tax incentives and the R&D tax credit, for instance, and assumes that these will create a supply response to support the needed talent base. But this indirect approach has had only a limited effect. We need a new incentive system aimed at the primary supply mechanism within universities.

It's also critical to address the broken workforce education system for the technical workforce. Improving the skills of these technical workers in order to meet the needs of employers that offer high-quality jobs now going unfilled needs to be a top education priority. As important as STEM education is, this focus has become an even higher priority. In one sector after another, from health to retail to construction to manufacturing, there is a growing need for stronger workforce skills. Yet the US suffers from a deep disconnect between its worlds of learning and work—education is simply not well connected to work and careers.

We need a range of initiatives to rebuild our broken workforce education system: short technical courses that are stackable and lead to both degrees and industry-recognized certificates; programs at community colleges that also reach high school students and incumbent workers; apprenticeships that combine on-the-job learning in quality jobs with technical education; new education technologies that will enable scaling up existing workforce programs; and new curricula that can train for advanced skills in emerging areas.

We need to unify historically separate Labor and Education Department programs so that they become complementary and reach incumbent as well as new entrant workers so they can develop new skills. We need universities that embrace their potential

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role in workforce education, rather than just assuming that it's someone else's job, and support lifelong learning. We need an expanded employer role in supporting curricula, apprenticeships, and new skill standards. And we need much better workforce information for employers, workers, and educators in our inefficient and decentralized labor markets.

Innovative new approaches, more or less advanced, are already being developed in all of these areas. Now we need to scale them up.

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12 EMERGENCE OF INDUSTRIAL INNOVATION POLICY

Industrial policy has long been taboo in the US outside the defense sector. For three years between 2020 and 2023, though, the federal government pursued a set of new industrial innovation policies at a level never previously attempted.[1] This was driven politically, largely on a bipartisan basis, by concern over China's extensive industrial policy system, which has enabled it to surpass the US as the world's leading industrial power. China is also beginning to outinvest the US, long the leader, in research and development (R&D) and critical technologies—directly taking a role that has been central to US innovation, and thus to economic growth and national security. Growing concern about climate change has also been a major driver for these new policies, as has the COVID-19 pandemic, particularly during 2020 and 2021.

This chapter places these new policy approaches into a historical context both in the postwar and in a series of subsequent periods, particularly emphasizing industrial policy approaches to the innovation system, reviews the definitional and economic debates over industrial policy, and then discusses these new approaches. The approaches in effect define a new toolset for industrial policy.

THE EARLY HISTORICAL CONTEXT

Like many innovation topics, this one begins with Alexander Hamilton, the first American leader—as the new country's inaugural Treasury Secretary—to back a federal role in industrial policy.[2] In his report to Congress on manufacturing and subsequent work, he advocated nurturing American industries through protectionist tariffs and direct support of industry.[3] Hamilton's tariff-based trade policies became a mainstay of federal government industrial policy for more than a century.

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Later, Hamilton joined President George Washington in supporting government-owned industries through the creation of military arsenals to produce weapons for the army.[4] The system of military arsenals was expanded a few years later to include government-owned shipyards that built the early US navy. The arsenals and shipyards marked the federal use of a defense justification for industrial policy. In making muskets, the arsenals at Harpers Ferry, West Virginia, and Springfield, Massachusetts, subsequently developed the first system of interchangeable machine-made parts, as noted in chapter 9; this system spread across early factories in the Northeast in the 1840s and was a critical step in enabling American mass production.[5]

Hamilton's plans were opposed by agriculture-oriented Southerners led by Thomas Jefferson and James Madison, and more direct support of civilian-sector manufacturing was not taken up by the federal government. Instead, Hamilton launched this branch of his industrial policy approach not through federal but through state support of a corporation developing water power at the Passaic Falls in Paterson, New Jersey, which supported a network of factories built around that power source.[6] These patterns of federal support for industrial policy—support for trade policy and for military R&D and industrial facilities, but not for direct civilian-sector industry involvement—proved long-lasting.

There are other historical currents as well for understanding American attitudes to industrial policy. Hamilton's Federalist Party evolved into the Whig Party in the 1830s, and it backed an agenda of government support for what that party called internal improvements—canals, roads, and railroads—at both the federal and state levels, as well as a central bank to promote sound fiscal policy. To entice investment in these improvements, states often bestowed monopoly rights on the risk takers; these tended to go to established figures from the monied classes. The Whigs were fought by President Andrew Jackson's Democrats, who favored democratic egalitarian ideals, closed the central back as a hallmark of privilege, and sought to end government monopolies in favor of all-out, unfettered competition.[7]

Corporations evolved by the mid-nineteenth century, at first in part as a way for government to charter and manage infrastructure projects for public needs, such as steamship routes or railroad segments. But the corporate model took off, shaking off its connection to government policies in the second half of the century, particularly with the rise of railroads. Federal subsidies for infrastructure grew with the transcontinental railroad acts at the same time that corporate power expanded, which initiated another generation of battles against unfettered corporate power through antimonopoly and regulatory movements.[8] In this period, the roles switched: corporations adopted Jacksonian-era views against government controls, while populists shifted to support of those controls. Today,

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both Hamiltonian and Jacksonian attitudes survive in attitudes about a governmental role in industrial policy.

During World War II, Vannevar Bush, President Franklin Roosevelt's science advisor, led the creation of a highly connected system for technology advance (detailed in chapter 3). The title of his policy tract, "Science, the Endless Frontier," was designed to appeal to the American sense that opportunity beckons at the frontier.[9] His approach enabled the federally funded research university to be initiated at scale, and these universities were closely linked to industry, the military, and government agencies. Federally Funded Research and Development Centers (FFRDCs) were created as well, and these elements led to critical wartime technology advances at the Rad Lab at the Massachusetts Institute of Technology (MIT) and the Manhattan Project. It was an intense system of industrial policy designed by Bush and other technology leaders to win the war. Immediately following the war, as detailed in chapter 3, Bush led the dismantling of much of this extremely successful connected system. In "Science, the Endless Frontier," he recommended a focus on basic research within a disconnected system.

Why? With the war machine being dismantled in the expectation of world peace, Bush likely was trying to salvage some parts of the system. He saw the power of the federally funded research university and advocated federal support for basic research that could sustain that creation. Basic research is far cheaper than applied development, and he likely thought the government could still support that basic stage amid the postwar cutbacks. He also was concerned that science, like Icarus, was moving too close to the Sun—science had become too tied to government, with all its intense political and military power, and he wanted to shield it, reclaim its independence. As detailed in chapter 3, Bush advocated what was later called the "pipeline model" for innovation, with early-stage research as the federal input into the pipeline, with the later pipeline inputs relying on industry. The model disconnected the actors in that innovation system. Like the king's horsemen with Humpty Dumpty, the US has never fully managed to put the pieces together again.

INDUSTRIAL POLICY FOR WHAT? THE DEFINITIONAL DEBATE

A preliminary question concerns defining industrial policy. In 2013, a British economist broadly defined it as "any type of intervention or government policy that attempts to improve the business environment or to alter the structure of economic activity toward sectors, technologies or tasks that are expected to offer better prospects for economic growth or societal welfare than would occur in the absence of such intervention."[10] More

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recently, another analyst defined industrial policy as "a set of policies and programs explicitly designed to support specific targeted industries and technologies."[11] In this sense, there can be multiple industrial policies to meet a variety of goals—including US international competitiveness, especially in advanced technology sectors.[12]

Others have tried to apply the term "industrial policy" to goals that are more about social policy, taking up the "societal welfare" element to advocate for "mission-based innovation."[13] This approach seeks to apply technological innovation not only to technological challenges but also to societal missions such as reducing economic inequality and building sustainable development—and puts forth the Apollo Moonshot project as an organizational model for how to get there.

Such advocacy for an industrial policy that addresses societal welfare poses the question of industrial policy's purpose.[14] A report from a liberal think tank provides a good example; it advocates industrial policy that would be aimed at the services sector because that work "is disproportionately female" and "where we see higher shares of people of color."[15] Yet service sectors are also the home of the nation's lowest-wage, lowest-quality jobs, so why not focus instead on *technology* sectors that offer high-quality jobs and work to expand desperately needed workforce education so minorities can better access those quality jobs?

The political economist Suzanne Berger argues that such advocacy reaches too far.[16] Technology programs such as the *Apollo* mission or the Manhattan Project were organized around technology goals, not broad societal goals—rocketing to the Moon or creating atomic weapons, not solving economic inequality or other societal goals. Putting societal goals ahead of technology development goals for industrial policy risks political disarray and is simply impractical.

What Berger is saying is that the term "industrial policy" has to emphasize *industrial*. Going beyond that adds a major political dimension that requires widespread public consensus for long-term, sustained political change.

Growth economics has long established that technological and related innovation is the largest factor in economic growth (discussed in chapter 1)—which, in turn, is a major enabler of societal economic well-being. But some specific societal goals are more in the range of a technology strategy than are others like developing energy technology, which addresses climate change, or implementing advanced manufacturing technologies to make the manufacturing sector more competitive that also retains manufacturing jobs.

Often driven by external crises, the federal government has periodically and actively sponsored industrial policy approaches. Societal welfare has typically not been the stated goal, but it can be a by-product; rather, the goals are typically narrower sectoral or technology targets or economic goals, such as improving economic competitiveness. That

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said, no one who has spent time in the industrial Midwest, with its swath of closed auto, steel, and other factories and the corresponding social nightmares to which such closings can lead, can argue that an industrial policy based on restored competitiveness is without societal justification.

Historically, the US has pursued many industrial *economic* policy–type approaches in areas such as transportation and energy infrastructure, healthcare delivery through medical benefit programs, and agriculture infrastructure and price supports, with government involvement through subsidies, contracting, regulatory, and tax policies that in turn affect technology deployment. These industrial policy interventions have been in particular economic sectors and involve deploying available technologies to further governmental policies.

Industrial *innovation* policy is somewhat different. It focuses on the government role in fostering innovation approaches within the broader industrial economic policy context, such as support for advanced manufacturing technologies and processes. Industrial innovation policy includes a governmental role not only in research but also in the later-stage development and implementation of technology innovation.

Industrial innovation policy plays out within the well-known stages through which a technology must advance: R&D, technology prototyping, testing, demonstration, product development, production financing, market entry, and expanded market creation. It entails government intervention in one or more of these stages to further a technological advance. The science and technology organization of World War II, for example, which knitted government, industry, and universities together with interventions at all these economic stages, was the result of a clear industrial innovation policy to meet wartime needs.

Industrial innovation policy goes beyond the "moonshot" approach that some call for, which follows a relatively straightforward government-contract model; the government issues contracts to firms and organizations to create the technology to get us to, say, the Moon. Many industrial policy approaches, however, also require that new technologies be developed, adopted, and embedded in the far larger private sector, a much more complex technology organization and system effort that requires major public-private collaboration. Energy and related climate challenges, for example, fall into this category. We also need to keep in mind that industrial policy can involve a range of implementation approaches.

Chapters 1 and 2 of this book recounted the economics theory behind the strong opposition to industrial policy that has come from neoclassical economists in the past. They have embraced certain governmental interventions when there is "market failure"—when, for example, the risks or costs of an activity are too high for the private sector to

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manage or there is a problem of collective action, as in public education, transportation infrastructure, and early-stage research. But technology development and its implementation are not on this list. Despite the success of several East Asian nations in applying industrial policy approaches, American economists continued to avoid it.[17]

Part of the reluctance of mainstream economists with respect to government intervention comes from the limits of their emphasis on mathematical economic modeling of markets and their efficiency, as well as their inability to model and therefore understand innovation and the complex systems behind it. Innovation requires the consideration of many complex elements outside of scientific advances that are not readily amenable to economic modeling, such as culture, traditions, vested political interests, change agents, governmental infrastructure, public expectations, collective action, and organizational management.[18]

Nevertheless, the federal government has since the end of World War II moved through four somewhat discernable periods of industrial innovation policy approaches. In each one, it has tried to reconnect—at least partially—the various actors in the US innovation system in industrial stages beyond research.[19] These four periods, discussed in detail in chapter 4, began with a *first period* during the Cold War that firmly established defense industrial innovation policy but did not do the same for civilian industry. Beginning around 1950, the military worked to integrate key innovation actors—industry, university, and government—in service of the defense mission, which ultimately led to the creation of the National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency (DARPA), both in 1958.[20] The scope of the Cold War threat forced the US Department of Defense (DOD) to return to the connected approach of World War II.

The *second period* was the era of manufacturing competition with Japan in the 1970s and 1980s, when Japan's economy advanced in leaps and bounds with the modernization of its industrial production process, the total quality management revolution—and the US found its industry comparatively disadvantaged by a lack of government coordination of innovative activities and actors. US industry was forced to play catch-up as it climbed the steep learning curve to embrace total quality production and management. This was the period of novel policy attempts (also detailed in chapter 4) to help small, innovative firms and start-ups at the cutting edge of technological innovation to grow and compete in global markets.

The *third period* began around 2001, with policy efforts to mitigate climate change through energy innovation at the US Department of Energy (DOE), as detailed in chapter 10. And a *fourth period* has evolved in recent years around advanced manufacturing, as reviewed in chapter 9.

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The success of industrial innovation policies over these four periods has been mixed, with many successes on the defense side but a mediocre record for demonstration projects motivated by energy policies.[21] Several past energy projects faced massive cost overruns in the past or were otherwise unsuccessful; among the most visible setbacks was when DOE made a $535 million loan guarantee to Solyndra in 2011 to scale up advanced solar technology that could not compete with the low-cost, subsidized panels put into the US market by Chinese firms, and Solyndra went bankrupt.[22] This highly publicized episode was embarrassing for those advocating industrial policy approaches, and problems like Solyndra remain a warning for those attempting to set future federal industrial policy.

THE DRIVERS OF NEW POLICY

A number of new industrial policy efforts took shape between 2020 and 2022 that were dramatically different in size and scope from what has been previously attempted in the US.[23] This was enabled in part by a major shift in government fiscal policy that created a rather abrupt outpouring of billions of dollars to drive industrial innovation policy. There were three drivers of new policy in this period.

The first was the COVID-19 pandemic, which killed more than a million Americans between 2000 and the end of 2022 and drove industrial innovation policies for the development and deployment of new vaccines. In March 2020, when it became clear that COVID-19 would unleash a worldwide pandemic, stocks fell almost as deeply as they had in 1929 and 1987. At a low point on March 23, US stocks lost 30 percent of their value and equities lost $26 trillion globally.[24] Even more ominous was that the market for Treasury bills was becoming illiquid and dysfunctional. The danger seemed to surpass that of the 2008 crash before the Great Recession.

The Federal Reserve (Fed) led other central banks in a rapid, three-pronged response: it created a loan facility to support credit card, auto, small business, and student lending; it took the unprecedented step of supporting direct credit to large employers by buying debt or loans directly from corporations; and it supported the public debt markets for state and local governments. Supplementing the Fed's efforts, President Donald Trump's administration backed a $1 trillion COVID relief bill in 2020, and the succeeding administration of President Joe Biden followed with $1.9 trillion in 2021. Once investors understood the scale of these dramatic steps, markets rapidly stabilized. Industrial policy programs in the following two years were pulled along in the wake of these major federal economic and pandemic funding commitments.

The implications of COVID-19 for future industrial policy lie in what the future holds. Going into COVID-19, the US had a reputation as the world's best-prepared nation for

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such outbreaks—a reputation that was shredded during the pandemic. The operating assumption of the American public by the end of what appeared to be the most acute phase of the pandemic in 2022 was that it would be a once-in-a-lifetime development, comparable to the 1918–1919 Spanish flu pandemic. Most felt that we would be all right for another century now—a view contradicted by the new realities of global connectedness that drove the pandemic's spread.[25] An ongoing threat of global infectious disease outbreaks, therefore, could become a *continuing* driver for industrial policy efforts.

Climate change is a second policy driver. The risks have become increasingly apparent through the increasing intensity of disruptive events such as wildfires, droughts, and hurricanes. While political resistance to recognizing climate changes persists in the US, precluding national political action on economywide carbon pricing and cap-and-trade legislation, there has been a shift toward grudging political support for a technology policy approach to climate, leading in 2021 and 2022 to major legislation incentivizing the entry of new energy technologies. This technology policy approach is offsetting the problems of reaching agreement on a carbon pricing policy approach.[26]

Finally, there is the challenge of China's technological advancement—the third driver. That this became a driver is linked not only to spending related to COVID-19 and its economic impacts, but also to the Trump administration's spending more broadly—including major tax cuts passed without spending reduction offsets. This signaled that at least part of the Republican Party had temporarily abandoned its longstanding fiscal conservatism. Other areas of federal spending opened up in the name of recovery, including industrial policies thought to be required to compete with China, which was spending massively on its own industrial policy efforts.[27]

China's entry into the World Trade Organization in 1999 sparked a major expansion in an era of global economic integration, but since 2008 that trend has reversed.[28] A new international system is emerging based more on global clusters, with major consequences for innovation policy. The COVID-19 pandemic taught lessons about the dangers of depending on global supply chains, providing a corresponding impetus for the domestication of supply chains and national supplier systems; these widely perceived COVID lessons were heightened by growing international conflict, led by Russia's invasion of Ukraine in February 2022. Today, older ideas on organizing industry like just-in time inventory and abandoning nonessential elements in favor of an emphasis on core competencies are being replaced by concerns about resiliency and more vertical integration.

The fading post–Cold War consensus about world economic integration has underscored views in the US about the need to reestablish domestic supply chains and manufacturing leadership. There is an increasing understanding that technology leadership drives national security leadership. Manufacturing is at last being understood as the

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crossroads between national security and economic security, and the three are increasingly seen as interdependent.

China's new ascendancy—including its major new applied technology programs that exceed US funding levels in semiconductors, artificial intelligence (AI), and advanced manufacturing—has led to a perceived technology challenge in the US, motivating industrial policy approaches. While China's growth rate declined in the post-COVID period, its manufacturing economy and investments in technology projects remain massive. These three policy drivers, which are likely to endure, have led to a set of *new approaches to industrial innovation policy* that we have seen emerge in the US in recent years. The sheer magnitude of the efforts associated with these approaches is far beyond anything previously attempted outside the defense sector. Combined, fully implemented beyond the examples given next, and adequately funded, they could signal a major policy turning point and constitute a fifth *period* of industrial innovation policy, in addition to the four discussed here—and a more systematic one. What follows is a summary of the major new initiatives and the seven underlying approaches to industrial innovation policy that they exemplify.

TOP-DOWN APPROACH

Nearly all the historical industrial policy approaches from 1957 through 2019 described previously were driven by crises. So was the effort beginning in early 2020 to develop a vaccine for COVID-19, known as Operation Warp Speed (OWS); it was in response to a massive crisis that emerged suddenly. OWS involved the implementation of a new *top-down* approach to industrial innovation policy that is almost universally acknowledged as a major accomplishment, thereby showing the potential of such an approach. It offers important lessons for other industrial policy efforts, and the wide-ranging toolset of OWS is potentially relevant to other industrial innovation efforts.

Organizationally, OWS was a wholly governmental, cross-agency partnership involving multiple departments and agencies. It gathered a *team* of first-rate, dedicated officials assembled from across the government, led by a former senior pharmaceutical executive and a US Army logistics general. This group operated as a change agent at rapid speed to respond to the national crisis, cutting across bureaucratic lines and taking advantage of diverse agency expertise and legal authorities. It was, as Dr. Matthew Hepburn, the OWS lead for vaccine development, put it, "inspired by DARPA but with a focus on scaling and implementation. OWS was DARPA at scale."[29]

OWS took a page from DARPA and decided on a *portfolio approach*, building on prior research on messenger ribonucleic acid (mRNA) and other vaccine approaches. The

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portfolio approach allowed for managing the technology risk and selecting a range of technologies and firms.[30]After reviewing more than 100 pending vaccine projects, three vaccine technology platforms were selected and then two companies were picked to support each of these platforms. OWS was picking winners: it made these selections based on which companies it believed were furthest along and most able to develop the various types of vaccines. The effort was not a public-private *partnership*; rather, it was *directed at* and included *collaboration* with *committed companies* in the private sector—especially with committed leadership at committed companies such as Moderna, Pfizer, and BioNTech.[31]

These components—the particular team that was built, the way the private sector was involved, and the portfolio of winners picked by the government—are what define this approach as "top-down" in this discussion. Chapter 8 detailed all these components of the OWS effort, as well as the set of tools employed that is relevant for other such efforts, which includes:

- Guaranteed contracts
- Flexible contracting mechanisms
- Technology certifications
- Mapped supply chains
- Diverse talent from across skills and fields
- Federal officials integrated with companies
- Cross-agency collaboration
- Accelerated distribution systems

Contracting was a critical OWS tool: both *guaranteed contracts* and *flexible contracting mechanisms*. The selected firms received guaranteed contracts to purchase substantial volumes of their vaccines despite that they weren't yet fully developed or approved by the US Food and Drug Administration (FDA). This allowed further development and clinical trials and assured that doses would be ready as quickly as possible. The government guarantee to purchase the vaccine at scale enabled purchasing supplies, developing production facilities, and scaling up production and distribution as soon as they were approved. The government's guarantee that it would purchase the vaccine at scale enabled the firms to take the risk of ordering supplies and developing production facilities and was vital to scaling up rapid production. This ability to provide contracts to assure an initial market and therefore reduce the risk of scale-up is a mechanism with potential applicability to other health challenges, as well as to other technology development fields.

OWS also made extensive use of *flexible contracting mechanisms*. The Defense Production Act was employed because it allows the federal government in national emergencies

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to require suppliers to supersede serving their existing customers to meet security needs. As chapter 8 has detailed, OWS also intervened directly when necessary under the act to help with producing, building, or refurbishing production plants, purchasing and fitting out equipment, hiring staff, enabling raw material supplies, and purchasing vials, syringes, and needles in bulk.[32] This decidedly top-down element of the OWS approach was key to lining up supplies and resources for vaccine makers to avoid production delays. The ability to intervene to assure secure supply chains is also relevant to other technology development projects to further industrial innovation policies.

The Other Transactions Authority (OTA), first developed by DARPA and used by DOD agencies, offered a way around the extraordinarily slow-moving process of normal federal procurements that could have sunk the OWS efforts, reducing the time to a contract agreement to days and allowing greater involvement of biotechs and smaller suppliers that don't typically work with complex federal contracting. Again, this authority is broadly applicable in other technology areas.

Technology certification was also an important element. The FDA's Emergency Use Approval (EUA) enabled it to do just that—to meet emergency needs like the pandemic without the usual full approval process, which can take years. This FDA step was critical, amounting to a technology certification and validation of the technology, ensuring instant market acceptance. Because FDA approval is the most respected approval for medical products worldwide, most of the American public immediately accepted the FDA-approved vaccines for COVID-19 as soon as they were available. There is no technology certification at all equivalent to that of the FDA for medical products in other areas, which amounts to a gap in the innovation system. But the federal government could use its strong lab network to undertake technology certifications to help ensure earlier market acceptance in a range of technology areas.

The Defense Production Act enabled OWS to intervene into supply chains, but key to that was an in-depth understanding of every facet of relevant supply chains. *Mapping supply chains* was another important task. The DOD's logistics experts, fluent with emergency logistics crises, understood supply chain reliability and how to map these chains. It greatly helped the vaccine companies with the intense supply issues that they faced in vaccine production. The techniques for supply chain mapping could be systematized and used to create resilience in a host of technology development efforts.

OWS also set up the *integration of federal personnel with companies*. It put federal agency personnel into a number of companies to help them with the complex regulatory approval processes, as well as project management and supply access. In addition, the Army Corps of Engineers oversaw construction to expand company production facilities.[33] The linkage with government personnel did not compromise the regulatory

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process at all, but it did cut bureaucratic barriers and accelerated processing. This is an approach, with appropriate conflict of interest safeguards, that could be more widely employed to speed critical technology development.

Finally, concerning *distribution systems*, OWS took on the task of getting vaccine doses shipped to states, setting shipment priorities based on a state population–based formula. The two mRNA vaccines from Pfizer/BioNTech and Moderna, which predominated, were particularly difficult to ship because they had to remain frozen and required special, complex handling. While the military helped boost distribution at occasional crisis points, OWS relied on efficient private-sector shippers for delivery. Only a tiny amount of vaccine ended up spoiling during shipment. Actual administration of the shots was left to states and their public health officials at their insistence. While in many states this was problematic and actual vaccinations lagged well behind deliveries, over time this issue was straightened out. In the end, the US led vaccine development and distribution, many weeks ahead of its developed-nation counterparts in the European Union (EU). The lessons from OWS on distribution organization and efficiency can also be more widely employed in technology development efforts.

OWS was not about science research; that work was largely completed by the time that that program began. But it did set a new standard for rapidly scaling up a technology into final development, manufacturing, and widespread use. While the DOD often undertakes this kind of effort, OWS was largely unique for nondefense areas. As Hepburn pointed out, it was like a DARPA for scale-up. It revived interest in the US in industrial policy, lifting it out of its long-dormant status as the bane of mainstream economists. It represented a strong and remarkably successful industrial policy approach. To reiterate, each of the major tools that OWS employed has the potential for application in industrial innovation programs.

Unfortunately, the Biden administration shut down OWS when it came into office in 2021, although some of its tools were still needed for pandemic management and its approach—including industry collaborations—could have been applied to other major medical needs. Keeping it going would have offered further proof of this top-down approach as one model for the range of capabilities that can be deployed. While in 2023 the Biden administration, seeing the gap from prematurely ending OWS, attempted to revive OWS's authority through its Project NextGen, the project was underfunded, and it was not clear whether it would have enduring Congressional support.[34]

BOTTOM-UP APPROACH

Government support for businesses is one of the most politically contentious issues in American policy debates. Opponents on all sides of the political spectrum argue that it

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can give an unfair advantage to one company or a few companies and skew competition, and, generally, that government has never been good at picking winners. The Solyndra example speaks to these problems: the company received DOE loans for its production and then failed during the early years of President Barack Obama's administration, which triggered a sharp political attack on government lending.

The department's loan program continued, though, and in 2022 was significantly expanded through the Inflation Reduction Act (discussed later in this chapter). Tesla, the first major electric vehicle (EV) maker, had been a major beneficiary of the program; it received a large DOE loan—critically important to the company—that was approved in 2009 and available through 2013. By the end of 2021, Tesla had reached a market value above the combined value of its five largest competitors.[35] By 2022, it was producing close to 2 million EVs a year.[36]

In fact, Tesla is a good example of how a company—and a sector of the economy—can benefit from government support,[37] in this case part of a *bottom-up* industrial innovation policy approach undertaken for a climate change mission of promoting EVs. Unlike with OWS, the government role in supporting EVs was not *top down*; it did not select a portfolio of winners to receive support in a series of key technology areas. Rather, the strategy was more *bottom up*; it created a menu of incentives and then relied on firms to come to the table and take advantage of them. In the specific case of Tesla, government did not drive the creation of the company, but the company enjoyed government incentives, loans, and regulatory elements, systematically, to help it overcome barriers and assume leadership in EV production. These mechanisms were more or less direct.

The direct category includes *lending*, as noted previously, in the form of the $465.5 million DOE guaranteed loan, authorized to Tesla in 2009 as part of the Advanced Technology Vehicles Manufacturing program to build its factory in California.[38] This loan, which Tesla paid back in 2013, helped rescue the company from near-bankruptcy.[39]

It also includes *subsidies*. Tesla has received about $2.4 billion in subsidies, largely from US states (and not including the repaid loan or the EV credits described next), including as just two examples about $1.3 billion in benefits for its Gigafactory in Nevada for battery production, and $750 million for its New York solar panel factory (Tesla integrates its vehicles with solar and storage technologies). Tesla laboratories have received about $3.6 million in subsidies and loan guarantees, and the company has also obtained governmental support from nations other than the US where it produces vehicles, including China and Germany.

Other government support has come in the form of federal programs that have aided Tesla indirectly, but also substantially. For instance, *tax incentives to consumers for purchase of EVs* have clearly helped spur Tesla's sales.[40] In fact, the first federal tax subsidies of $7,500 per vehicle to help boost EV sales, initiated in 2008 and 2009, reduced the cost

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of the first 200,000 Tesla vehicles by a whopping $1.5 billion. This consumer tax credit was renewed without the 200,000 car limit in 2022 for EVs built in the US. In addition, the federal government provided (and the Inflation Reduction Act of 2022 extended) a tax credit of up to $1,000 for EV-charging hardware (totaling $1.7 billion) for consumers and $30,000 for commercial installations. And 2022 infrastructure legislation contained $7.5 billion for the deployment of half a million charging stations nationwide. Tesla, as the leading US producer of EVs, will be a major beneficiary of this *infrastructure support*, which expands its existing network of charging stations.[41] Each of these tools are potentially applicable outside the energy sector to other technology development projects.

To these federal programs must be added *state regulations and incentives*—particularly in California, where clean air regulations and incentives have supported substantial subsidies for EVs over time, which has been of particular benefit to Tesla. For instance, California's *EV mandate and offset payments*, a state program for credits for EVs paid by other automakers not making these cars, resulted in payments to Tesla of nearly $4 billion from 2019 to 2021—a substantial part of the company's profits.[42] These payments have been important to its ability to scale up production. In addition, California has, since 2016, offered *rebates* to consumers who purchase EVs, up to $7,000 for EVs, based on income eligibility.[43] An earlier version of the rebate program amounted to $2,500 per Tesla vehicle, helping to build its customer base.[44] The Tesla experience indicates the potential value to technology development efforts of state regulatory programs that parallel federal goals.

The less-direct category—meaning that the government support was not directed specifically *to* or *at* Tesla—includes *early-stage R&D support* by DOE for the development of improved lithium ion (Li-ion) battery technology—along with a number of new programs for applied R&D for EV batteries since 2020. As in so many industries (pharmaceuticals being a key example), private companies can benefit tremendously from such programs. Since batteries are an EV's engine and by far its largest cost element, this support is potentially critical to EV makers, including Tesla.

DOE has funded a range of R&D projects, including for advancements in batteries for EVs, in lightweight materials, and in new mobility systems. Tesla could be a beneficiary of R&D advances that may emerge from DOE's Energy Storage Grand Challenge, announced in January 2020. It was the department's first comprehensive strategy based on what it calls "innovate here, make here, deploy everywhere." Performance targets include cost reductions (from 2020 costs) of 90 percent for stationary applications and 44 percent for battery packs in EVs.

Tesla and other companies could also be significant beneficiaries of what comes out of the Federal Consortium for Advanced Batteries (FCAB), a consortium of federal agencies

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for cross-government cooperation. In 2021, the consortium released a National Blueprint for Lithium Batteries 2021–2030, which laid out five critical goals that cover the entire spectrum of R&D and innovation, including developing a strong domestic lithium-processing sector, enabling end-of-life reuse and recycling, and advancing US leadership in battery technology by supporting R&D and science, technology, engineering, and mathematics (STEM) education.

As with these examples, Tesla and the broader EV industry could also benefit from Li Bridge, a government–business sector partnership to close gaps in the domestic lithium supply chain. DOE coordinated its formation in 2021 through its Argonne National Laboratory and has provided $209 million in funding for twenty-six EV battery projects on the "cost and size of next-generation battery technology, fast charging EV infrastructure advancements, potential grid impacts of EV charging, and cooperative vehicle-to-vehicle communications and controls that reduce energy use and emissions."[45] And there is the $3 billion in support for battery development and production for vehicles and storage as part of the $1.3 trillion federal infrastructure package enacted by Congress in 2021.[46]

In summary, in the context of an industrial innovation policy (even if not explicitly identified as such) aimed at supporting the expanded use of EVs to mitigate climate change, the government took bottom-up steps that supported (both directly and indirectly) a key company in that sector—even rescuing it from bankruptcy. This support enabled it to build key production facilities, subsidized consumers to purchase its products, supported a massive build-out of charging station infrastructure, and fostered advances in EV battery technology. Thus, governments (primarily federal, but also state) have been important supporting partners at every stage. These mechanisms are relevant to technology efforts outside the energy field.

The investments have had major consequences. Putting aside the persistent controversy that has surrounded Tesla's cofounder Elon Musk, the company has successfully demonstrated to the American and world public that EVs work. Tesla has also almost single-handedly driven all the world's major auto producers to commit to a future of battery-driven EVs, displacing more than a century of fossil-fueled internal combustion engines. That supports the government mission explicated earlier.

From a policy perspective, this example demonstrates that a *variety* of approaches to industrial innovation policy exist. While support for OWS was top down, involving government picking a portfolio of winning companies that offered a range of vaccine technologies, support for EV development was bottom up, with government creating incentives and supportive research programs and leaving it up to the private sector—with Tesla as the leading company—to drive economic development.

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The year 2022 provided another major example of the bottom-up approach. In August 2022, Congress passed a massive energy and climate program within the Inflation Reduction Act. The bill's climate-related provisions will cost more than $375 billion in the form of tax and consumer incentives for electrification from clean energy technologies, electrification of surface transportation, and decarbonizing buildings and manufacturing. Among these provisions, the bill greatly expanded the DOE's loan authority by some $40 billion, through its Loan Programs Office, for energy technology firms, providing support for energy technologies, including manufacturing initiatives and greenhouse gas emissions reduction projects at industrial facilities.[47]

This maze of incentives and funding was projected to reduce US carbon emissions significantly, bringing it closer to the 2030 goal of a 50 percent reduction from 2005 emission levels.[48] The key industrial innovation features of the legislation, then, were tax and consumer incentives and production incentives to industry, at very substantial scale, to drive the introduction of new technologies. In addition, the lending authority could be key to scaling up energy technologies. The legislation clearly amounts to a bottom-up approach to industrial innovation policy at a level not previously seen.

DEMONSTRATION PROJECT APPROACH

The demonstration phase for technology development, which follows directly from developing a working prototype, is critical to industrial innovation policy. Only once a technology has been successfully tested and demonstrated can it be moved to the pilot production phase and ultimately scaled up to full production—firms cannot take the risk otherwise.

The DOD has long understood this, so it ensures demonstration phases for its emerging technologies—which has created deep experience with administering this phase, along with needed test beds. The DOE has not created an ongoing capability to manage demonstrations (especially where the commercial sector lacks the incentives to carry them out on its own)—but it will need to do so.

The massive 2021 infrastructure bill passed by Congress places strong emphasis on the demonstration stage of technology implementation and provides $21.5 billion in funding for these projects through a new DOE Office of Clean Energy Demonstrations. These include *carbon management projects,* such as direct air capture hubs and carbon capture demonstrations; *clean hydrogen programs*; *renewable energy programs*; nuclear energy programs for *advanced nuclear* reactor demonstrations; and demonstrations for *critical minerals* and rare earths.[49]

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Past problems with government demonstration projects provide three important lessons for adopting this approach to industrial innovation policy:[50]

• Indirect incentives (production payments, tax credits, loans or loan guarantees, and guaranteed purchases) for demonstrating the possibilities of new technology deployment to the private sector have important advantages over stand-alone, government-dominated demonstrations not well connected to potential users.

• Because large demonstration projects with large cash outlays attract congressional interference, creating a quasi-public corporation to manage the demonstration is a way to provide insulation against congressional intervention.[51]

• It is important to build flexibility and resilience into the economic model for demonstrations (as is often done effectively in the private sector), so the executors of the project can react to changing market conditions and design the demonstration to avoid the assumption that current economics will always continue—a mistake that has plagued so many past projects.

Managing a commercial demonstration requires management expertise that the private sector has and the government largely lacks. A public corporation could be a means to recruit people that do possess such expertise. A public corporation could also operate outside the limits of government procurement systems in an environment more comparable to that of a commercial firm. This private-sector expertise—in both major project financing and commercial-scale engineering—could be backed by the kinds of financial incentives described earlier, as well as by access to a sufficient multiyear stream of assured funding to permit the efficient execution of a demonstration project. Cost sharing with industry can provide a further incentive to cost control and commercial discipline.

Technology demonstrations constitute significant industrial policy. They will not work unless the government builds the management capacity to handle them.

DIRECT PRODUCTION SUPPORT APPROACH

Sometimes it's not enough to promote scale-up through guaranteed contracts, tax incentives, or technology demonstrations; *direct support of production facilities*—a step rarely taken by the federal government outside the defense sector—is needed. We find an example of this point in semiconductors, an industry that undertakes the most advanced manufacturing at what are by far the most expensive plants in the world. Policymakers found that for the US to retain even a modest level of advanced

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semiconductor production capability, governmental intervention to support production was needed.

The importance of having this approach in the industrial innovation policy toolset becomes clearer with a bit of background on semiconductors themselves, which are a foundational technology on which all software operates and data are processed. They are essential for defense technologies and systems and for upcoming generations of advanced technologies, particularly AI and quantum computing, which also have significant national security dimensions.[52] And, of course, they are core to a host of societal services, such as computing, the internet, and broadband, upon which the daily economies and functioning of societies are based. US technology leadership is essential for all these reasons.[53]

The US government is now undertaking its second intervention into the sector; the first was in the late 1980s, when the US semiconductor chip industry was falling behind Japan's leading firms, Nikon and Canon, which were working closely with Japan's industrial policy program through its Ministry of International Trade and Industry.[54] President Ronald Reagan's administration was convinced to back a public-private partnership, Sematech (a consortium of fourteen semiconductor companies cost-sharing with $500 million of DARPA funding), in an effort to restore US technology leadership.[55]

Sematech is generally acknowledged to have played an important role in the return of technology leadership in semiconductors to the US. It focused on chip manufacturing, and there was a major joint effort to improve the speed and quality of chip production systems. By 2020, though, after having offshored much of its electronics production, the US again faced a loss in chip leadership, to Taiwan, which faces a continuing threat of invasion from China, and South Korea, which were producing the most advanced semiconductors. The world has become largely dependent on one semiconductor maker: Taiwan Semiconductor Manufacturing Company, which makes 90 percent of the most advanced semiconductors only 100 miles from mainland China.[56] The loss of US leadership happened despite the fact that in 2019, semiconductors were still the largest US electronic product export and the fifth-largest export product in general, amounting to some $42 billion, and American companies—including those with production abroad—held 45 percent of the global semiconductor market.[57] But the share of semiconductors produced in the US had fallen by 2021 to only 12 percent, down from 37 percent in 1990, and none of these were the most advanced semiconductors.[58]

Meanwhile, China has been making massive investments in semiconductor technology since the early 2000s, essentially starting from zero, in a systematic effort to dominate the sector. While it does not have technology leadership, it now has a major presence in lower-end chip production and its investment level dwarfs that of the US.[59]

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While US *R&D and design capabilities* are still solid, the US is failing to translate them into production leadership in semiconductors, a problem that it has in so many other production areas—which is what elevates this discussion to the level of another approach to industrial innovation policy. In this particular case, production needs to be seen as part of innovation and is deeply tied to it (as discussed in chapter 9); production erosion leads to innovation erosion. In the semiconductor example, this is exacerbated by the fact that venture capital (VC) for semiconductor sector start-ups in the US has been available at the seed stage, but it is foreign capital that has dominated at the scale-up stage, when start-ups need to bring technologies into production and implementation.[60] On top of that, there is the question of where the trained talent is going to come from if the US is to restore its leadership in semiconductor technology. That is a *workforce* challenge with implications for educational programs that will be needed at both the electrical engineering and technician levels.

Alert to the security and geopolitical implications of these developments, Congress passed the bipartisan Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act in 2020, a major piece of legislation designed to restore US semiconductor technology leadership. It authorized $52 billion for government interventions in the sector, supplemented by a 25 percent investment tax credit and a $75 billion loan guarantee program. It was fully funded in 2022 (as part of the CHIPS and Science Act discussed next), with strong bipartisan support. While the funding level will not make the US the dominant production leader it once was, it should halt the erosion of its share of world semiconductor production.[61] The legislation may prove too little, too late, but it marked a major and direct government intervention into the sector at an unprecedented funding level.

The key provisions of the legislation lay out a road map of how this approach to industrial innovation policy fits other sectors where the same sort of governmental intervention might be needed. They include the following:

- *Direct manufacturing support* of $39 billion in the form of grants to construct, expand, or modernize domestic facilities and equipment for semiconductor fabrication, assembly, testing, advanced packaging, or R&D
- An *investment tax credit* and *loan guarantee* program for advanced production facilities
- A major $11 billion investment in *R&D*, including the establishment of public-private partnerships and government-industry-university centers and programs to strengthen US capabilities across the sector
- Creation of *manufacturing* institutes with a production innovation focus
- *Workforce education* focused on both engineering and technical levels

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- A focus on *international supply chains* through efforts centered around both the Departments of State and Commerce in the federal government

The direct competitive grant support for production facilities is the most significant departure in the legislation from prior policy. That makes it, in many ways, the most interventionist of the industrial innovation policies noted here, but such a step may be justified in the case of critical technologies, particularly those with national security aspects.

It is notable that the legislation engages at a series of technology development stages, consistent with the industrial innovation policy definition given earlier: at the R&D stage, to attempt to secure semiconductor technology leadership; at the supply chain level, with an assessment of supply vulnerabilities and international coordination; at the production financing level, to assure the location of semiconductor fabrication plans (known as "fabs") for producing advanced chips in the US; in the development of advanced manufacturing technologies for both chips and related packaging areas; and with a coordination element to attempt to secure Asian and European cooperation in the face of massive Chinese subsidies of its semiconductor sector, as well as cross-agency coordination. While the direct production support was the new feature, the legislation was more than that: it placed this production support within a *comprehensive* industrial innovation policy approach.

SUPPLY CHAIN APPROACH

In June 2021, the Biden White House, after 100 days in office, issued a major report in response to a prior presidential executive order on "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Foster Broad-Based Growth."[62] The Departments of Commerce, Energy, Defense, and Health and Human Services all cooperated in the report's development.

This was a planning project to be implemented in subsequent years. The report examined domestic supply chain gaps in four areas and made a long series of recommendations for bolstering supply chains in each one of them.

This effort underscores the government's involvement in industrial innovation policy. Some of the specifics for each of the four areas addressed—pharmaceuticals and ingredients, advanced batteries, critical minerals, and semiconductors—offer a look at the generalizability of this approach.

In *pharmaceuticals and pharmaceutical ingredients*, the US experienced serious supply problems for personal protective equipment and other needed medical supplies during the coronavirus pandemic, which led to a new awareness of supply chain issues in the

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medical sector. The report also found that the US had offshored much of its production capability for pharmaceutical goods and argued that more resilient supply chains, including improving supply transparency, building emergency capacity, and investing in domestic production, were required. Policy recommendations included using the Defense Production Act to set up a consortium for onshoring of essential medicines and supplies.

With respect to *advanced batteries*, which are integral to the technologies needed for a clean energy transition and national security capabilities, the report found that the nation's reliance on imports for the elements required for fabricated advanced battery packs exposed the nation to supply chain vulnerabilities that threatened to disrupt the availability and cost of the technologies that rely on them. It stated that investment in scaling up a secure, diversified supply chain is required, and recommended that DOE develop a National Blueprint for Lithium Batteries and a ten-year plan for lithium battery supply chains (which it has done).[63] It also said that DOE should develop a major lending program for domestic battery supply chains and launch a number of pilot battery storage projects at federal sites.[64]

The report found that even if the US diversified its sources of *critical minerals* or increased domestic extraction, it would still have to rely on China, which has captured large portions of the relevant value and accounts for an outsized share of the world's refining capacity. The report recommended that the US work with its allies to diversify supply chains, and also invest in sustainable domestic production, refining, and recycling capacity. In addition, there were recommendations to provide incentives for production and processing in the form of loans, grants, and federal purchase agreements, and to expand international investments in needed projects to ensure access.

Finally, there were recommendations regarding *semiconductors*. The report supported the steps taken by the CHIPS Act. The report also made clear that this was not to be the only supply chain effort, and the Biden administration subsequently established a Supply Chain Disruptions Task Force across agencies to address near-term supply chain challenges to the 2021–2022 economic recovery, with a focus on areas where supply-and-demand issues had become an economic problem in 2021: homebuilding and construction, semiconductors, transportation, and agriculture and food. This expanded the reach of the supply chain approach to industrial innovation policy. In February 2022, the White House issued a follow-on report with industrial base reports from seven agencies that were charged with tasks under the initial 2021 report.[65]

The planning efforts and the multiagency projects that grew out of it to build more resilient supply chains are a signal of a new level of government industrial policy involvement through supply chain mapping and interventions.

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COUPLING THE BASIC AND APPLIED RESEARCH APPROACHES

An underlying goal of what became the CHIPS and Science Act was to bring basic research into proximity with applied research to take advantage of linkages between the two. It marks a shift from the longstanding US basic research emphasis advocated by Vannevar Bush in 1945 (see chapter 3) to include more applied research.[66]

The legislation went on a roller coaster ride to be enacted. First introduced in May 2020 as the Endless Frontier Act (an homage to Vannevar Bush), it aimed "to solidify the United States' leadership in scientific and technological innovation through increased investments in the discovery, creation, and commercialization of technology fields of the future," in the face of advanced technology competition from China.[67] It was revised the following April and added full funding for the previously authorized CHIPS Act,[68] with a focus on new applied programs at the National Science Foundation (NSF) and the Department of Commerce, passing with bipartisan support in June 2021.

Meanwhile, the House Committee on Science, Space, and Technology passed somewhat comparable bipartisan legislation that placed less emphasis on technological competitiveness and more on societal goals.[69] In a way, the two bills presented aspects of the debate on "industrial policy for what?" discussed earlier in the chapter.

After a multimonth conference, the final compromis*e* legislation—largely merging the two approaches—passed in August 2022. It included both the CHIPS Act funding and major science provisions and was renamed the CHIPS and Science Act.[70] Its science provisions were authorizations, not actual funding appropriations, but it nonetheless spelled out a set of new industrial innovation policy thrusts. Despite bipartisan support, a divided Congress made it unclear in the two years after its passage whether adequate appropriations for implementation would follow.

The bill's many provisions, some of which are spelled out next, help explain why this is a new approach to industrial innovation policy. With respect to NSF, the legislation's key science-related provisions included a new agency focus, with the creation of a new Directorate for Technology, Innovation, and Partnerships at NSF, representing a break from the foundation's historic basic research focus to emphasize translational research that strengthens US competitiveness by accelerating the development of key technologies into science and engineering (S&E) innovations. The directorate was required to address "Societal, National, and Geostrategic" challenges ranging from national security and manufacturing to workforce development, climate change, and inequitable access to education and opportunity; as well as to support ten critical technology areas (subject to being updated in coordination with other federal agencies): artificial intelligence (AI), high-performance computing, advanced manufacturing, quantum information

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technology, cybersecurity, advanced communications technology, biotechnology, advanced energy technologies, disaster prevention, and advanced materials.[71]

This major step of adding an applied focus to NSF included three other elements:

- The establishment by the NSF directorate of *translation accelerators* with universities and industry to further the R&D and commercialization of the critical technologies
- The creation by NSF of *test beds* to advance the development, demonstration, and deployment of new technologies
- New NSF funding for semiconductor workforce education to support the CHIPS Act, and the expansion of NSF's Advanced Technology Education program for developing curricula and programs in advanced technologies at community colleges

Prior to the legislation's enactment, NSF had already embarked on an ambitious effort to form *regional innovation engines*. These were to bring an innovation economy to geographic regions left outside the nation's technological advances in an effort to create more geographic parity. Although NSF had little experience with fostering regional innovation, the new law codified NSF's regional effort.

To fill a long-standing US innovation system gap, there was also a new technology strategy effort that could also better link basic and applied programs, which includes the following:

- The development of a comprehensive, four-year *national science and technology strategy* by the White House Office of Science and Technology Policy (OSTP), which plays the government's cross-agency coordination role, and its submission to Congress. It was to reach across basic and applied lines, with a primary focus on economic security.
- The periodic development and updating by OSTP of a national security-focused science and technology strategy in support of the nation's existing National Security Strategy.
- A quadrennial review by OSTP of the nation's overall science and technology enterprise.

The provisions could all be important to US competitiveness. In addition, there were social goals: the legislation created and expanded NSF programs for broadening participation and diversity in science, for STEM education; and for a major expansion of a research set-aside program for research at less-established research universities. And there also was funding aimed at satisfying NSF's university basic research constituency.[72] The political risks of adding social goals to technology development legislation came to bear as the legislation progressed, reducing bipartisan support—particularly in the House of Representatives—for its final passage.

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The act also gave significant new responsibilities to the Commerce Department's National Institute of Standards and Technology (NIST) and Economic Development Administration (EDA):[73]

- The creation of *regional technology hubs* to focus on technology development and improving regional innovation capacity. These were in addition to NSF's regional efforts.
- The development of a *recompete pilot program* to support persistently distressed communities with economic development activities.
- Expansion, in the form of tripled funding, for NIST's *Manufacturing Extension Partnership (MEP)* program. MEP is cost-shared with states and assists small manufacturers in every state with improving manufacturing processes and technologies, including cybersecurity, workforce training, and supply chain resiliency.
- The creation of three new competitively awarded industry-university *Manufacturing USA Institutes*, with responsibility for production semiconductor technology development and expanded capacity for education and workforce development.

In addition, the act authorized more funding for DOE science programs, both basic and applied.

The importance of this legislation, with its overall aim of putting the US in a position to compete with major ongoing applied technology initiatives in China and despite having been watered down from its original conception and the uncertainty of follow-on appropriations, is considerable.[74] It concentrates attention in large part on NSF, the one major, broadly focused R&D agency in the US not tied to a specific, and narrower, mission such as health, energy, or defense.[75] While technology development has not been NSF's job, the CHIPS and Science Act establishes a technology-focused subunit within the agency—the new Technology Innovation and Partnership Directorate—and marks an attempt to link the basic and applied sides of research. Therein lies the reason why this rises to the level of a new approach to industrial innovation policy. And optimally, the Technology Directorate could form part of a larger system. The strategic planning requirements in the legislation could also help with basic and applied links.

Getting to new technology, as opposed to new science, requires moving through a series of postresearch stages, as noted earlier: development, prototyping, testing, demonstration, scale-up/piloting, initial markets, and full production. Nondefense legislation that recognizes the need for an innovation *system* is a significant new step, and this legislation attempts to create organizational elements aimed to match each stage of a systemic process. The challenge now is to link these new organizational elements and pull them into a new system.

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If the NSF can drive applied and translational technology as well as basic science—which may be a challenge given its basic research culture—and if it can create working technology accelerators and test beds despite its lack of experience with these approaches, it will provide important lessons about moving this approach forward.

REGIONAL IMPLEMENTATION APPROACH

The regional technology hubs called for in the CHIPS and Science Act, to be funded and set up through the Commerce Department's EDA and NIST programs, as well as the regional innovation engines under NSF, are new programmatic elements that could be a way to encourage regional innovation and address regional inequalities—another new approach to industrial innovation policy. Regional entities offer a way to move the flow of research from basic and applied stages into implementation, since innovation tends to scale up in regional innovation ecosystems, not at the national level.

To summarize a large body of literature in a few words, most believe that we need regional ecosystems for innovation to thrive,[76] and innovation clusters have been studied for years.[77] There has been considerable experimentation at the regional level, and some places have become hubs of innovation activity not simply by accident but through concerted effort, such as Pittsburgh and San Diego. Often these fail, however, particularly when innovation tasks are imposed on struggling regions that lack underlying innovation capabilities. No single recipe has emerged as the winning one.

Typically, a regional innovation ecosystem includes an education and research institution that serves as an anchor for technology research and talent. Ecosystems also seem to need an organized public sector deeply engaged with the private sector—including committed companies and area business groups—all pursuing a joint strategy.[78] Solid larger firms linked to solid supply chains of smaller firms are another ingredient. Regions need to build on their existing regional strengths—not every area is going to be a biotech hub.

Workforce education has become an increasingly significant component of a working regional ecosystem, so a number of regions are now encouraging companies and start-ups to come because they offer a trained and skilled workforce that's tied to employer needs. To summarize a few key points, there needs to be a big tent; that is, broad engagement in innovation, not a narrow, single-innovation focus. Strong locally based firms need to be engaged as anchor tenants. A connection is needed to the talent pipeline—state university and skills education programs, for example—that will be key to companies. And state and local governments need to strongly support the effort.[79]

Can NSF and the Department of Commerce create successful regional innovation centers that both enable technology implementation and assist in regional economic

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equality? This is a particularly difficult challenge. Some of these experiments will work; others may not. But with adequate funding, there should be important lessons learned from the effort.

SUMMING UP

While the DOD has long operated an industrial policy system with economic interventions at many stages of the innovation process, this is largely a new path for government in the civilian economy. There are, of course, historical precedents, including programs to respond to Japan's development of quality production technologies and processes in the 1980s, the development of energy technologies in the 2000s, and the effort to create advanced manufacturing institutes after 2012. But the plethora of new industrial innovation policies proposed between 2020 and 2022 and summarized in this chapter are unprecedented.

Some of these may not go into full effect because of funding issues. Others could amount to a new and larger-scale period of industrial innovation policy approaches beyond the examples offered.

In discussing these new approaches, one thing that becomes clear is that a number of key operational mechanisms will be required to organize them so they are fruitful. In effect, what is needed is a new supporting infrastructure. The US will need to adopt a "systems of innovation" approach and revise the old linear pipeline model. It will need to approach innovation in a dynamic way in terms of its interdependent components, flows, organizations, and underlying policies. It will need to look at barriers and bottlenecks to these needed flows, with collaborating agencies brokering solutions. A scattered agency approach will not be enough. It will need scale-up support.

Industrial innovation policy is a complex process with many actors, and it requires a careful plan, strong foundational programs, and a spirit of enterprise. It requires a new, sustaining infrastructure. As the Pentagon discovered long ago, you can't just build pieces; you must also build the system.

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13 TOWARD A NEW INDUSTRIAL INNOVATION POLICY INFRASTRUCTURE

The legislative and executive branch initiatives described in chapter 12 and characterized as *new approaches* all meet the definition for industrial innovation policy also spelled out in that chapter. They involve governmental interventions at a range of innovation stages beyond early-stage research—from development to prototyping, testing, demonstration, product development, production financing, market entry, and expanded market creation. As such, they forgo the straightforward government-contract model of the "Moonshot" approach, in which the government issues contracts to firms and organizations to achieve the technology. A contracting approach is inevitably limited by scale; efforts that combine public and private sectors can have more widespread economic effects. These entail government intervention in one or more of these stages to further a technological advance. The examples given for each of the new approaches all involve programs operating at different stages, but without exception, they all reach a number of postresearch stages.

These new approaches include top-down, bottom-up, demonstration project, supply chain, coupling basic and applied research, and regional implementation. Together, they amount to a new direction for the US in industrial policy. To take that direction and achieve the fundamental change that we need, however, there are some major system gaps that need to be filled.

SIGNIFICANT GAPS TO FILL

Two gaps stand out in particular. Let's explore them in further detail.

The first concerns *cross-agency coordination*. To understand this gap, consider semiconductor research and development (R&D), in which multiple US government agencies are already involved.

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While the CHIPS Act gave major responsibility to the US Commerce Department's National Institute of Standards and Technology (NIST) to administer much of the act's $52 billion for new facilities and R&D, it is the US Department of Defense (DOD) that has, in the past, led government efforts in semiconductors. These range from DOD's early role in creating the initial markets for logic chips to the role of the Defense Advanced Research Projects Agency (DARPA) in coordinating semiconductor design and support for Sematech, which helped rescue the industry in the early 1990s. In recent years, DOD has backed the creation of a "trusted foundry program" for producing chips for defense systems in secure US production facilities, and, more recently, a potentially more practical approach of "quantifiable assurance," working with semiconductor fabs to verify output quality.[1] Further, DARPA's major Electronics Resurgence Initiative, which began in 2017 to restore US technology leadership in microelectronics and semiconductors, spurred the CHIPS Act in many ways and is ongoing.[2]

Overlapping with NIST's programs under the CHIPS Act discussed in chapter 11, DOD in 2023 created collaborative university-industry centers for prototyping semiconductor advances (called "Microelectronics Commons").[3] DARPA is supporting industry-university prototyping for new three-dimensional heterogeneous integration technology for packaging chips to improve their speed and efficiency.[4]

Yet, under the CHIPS Act, NIST will be creating separate university collaboration centers through its National Semiconductor Technology Center (NSTC) program. NIST is also launching under the act its own semiconductor packaging and integration initiative. Other federal government agencies, including the National Science Foundation (NSF) and the US Department of Energy (DOE), are involved as well.

The R&D coordination role among agencies falls to the White House Office of Science and Technology Policy (OSTP), which can form committees around technology issues through the cabinet-level National Science and Technology Council that it administers[5] (and has done so with a semiconductor subcommittee). But OSTP doesn't play a direct role in setting the budgets of science agencies, so it lacks a key tool to ensure connections across these agencies. In addition, the agencies report back to the numerous, and separate, congressional appropriations subcommittees that fund them—and that will not tolerate that funding flowing from one agency to another.

The bottom line is that collaboration is not easy in the decentralized US government science system; in fact, interagency coordination in American governance typically seems like a contradiction in terms. Although such coordination is vital in the area of industrial innovation policy, we have only limited tools to ensure it.

There is no easy fix for this—the decentralized innovation agency structure is embedded into the established political governance system as well as into the congressional

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committee funding system. However, Operation Warp Speed (OWS) offers a possible coordinated approach. As discussed in chapter 12, OWS brought together officials from several health agencies and the DOD and merged them into a task force structure focused on rapid COVID vaccine development. A former industry vaccine development expert and a defense logistics general were specifically named to lead the project. The agency officials came together in the new OWS structure, under the secretary of the US Department of Health and Human Services (HHS), to build a common effort and program, reporting first to the management group formed specifically for OWS and not to their agencies. But they retained their agency positions, so they could go back and utilize their unique agency authorities and funding to serve the OWS mission. This kind of interagency task force, which represents an important new model for interagency coordination, could be applied to other technology development priorities requiring interagency collaboration.

The second major gap concerns *technology scale-up*, and specifically for financing technology scale-up—the stage following prototyping to where actual production commences. The mix of new post-R&D tools provided in the new approaches discussed in chapter 12 does not fill this gap. The CHIPS Act provides grant funding, loan guarantees, and investment tax credits for semiconductor fabs and foundries that meet various requirements, DOE has an expanded lending program, and OWS used guaranteed contracts. But the other initiatives have no comparable mechanisms. American venture capital (VC) typically does not fund this stage for so-called hard technologies, as discussed in chapter 10.

Compare this situation with that of China, which *does* fill this gap. China has a manufacturing-led innovation policy (like Japan, Germany, South Korea, and Taiwan, as discussed in chapter 9), while the US has research-led innovation. Also, unlike the US, China focuses on production scale-up as a critical innovation. In fact, no other country comes close to providing the level of China's support for industrial scale-up.

China's industrial policy tools include massive direct subsidies to its industrial companies, payments to state-owned enterprises, state investment funds, below-market credit, debt-equity swaps, below-market land sales, and tax incentives.[6] China's direct subsidies to firms include many advanced sectors, including semiconductors, technology hardware, advanced manufacturing, software, pharmaceuticals, energy, and materials.[7]

A 2022 report characterized China's industrial policy spending as "enormous," totaling 1.73 percent of its gross domestic product (GDP) in 2019 and equivalent to $407 billion in purchasing power parity exchange rates.[8] The US has no equivalent to most of the mechanisms that the Chinese employ.

China has been pursuing industrial scale-up since Deng Xiaoping became China's paramount leader in 1978. The only historical US comparison point to China's

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industrial rise in recent decades is the growth of the US industrial economy in the later part of the nineteenth century and early twentieth century.

Let's look in more detail at one of China's key industrial policy mechanisms—guidance funds—and see if it can fill a gap that hampers the US (namely, the fact that US VC is largely missing from the task of scaling up hardware technologies or capital-intensive advanced manufacturing).[9] These funds and how they work offer some important lessons for filling this gap.

China's industrial guidance funds are government-sponsored, public-private VC funds with two tasks: support industrial policy goals while providing investment returns. In one industry alone, semiconductors, an Organization for Economic Cooperation and Development (OECD) study found that guidance fund financing "profoundly reshaped" China's companies, finding a direct relationship between construction of new semiconductor fabs and equity financing from the government-supported guidance funds.[10] More broadly, the Chinese government in recent years has been driving investment away from internet firms, social media, and consumer services and into hard technologies,[11] and guidance funds have been a tool employed in that endeavor.

These funds bring a VC-like, profit-oriented, private-sector investment outlook to state-sponsored industrial policy and provide existing companies and projects with ample funding to move into large-scale production rapidly.[12] The funds are designed to offer patient capital, recognizing that a revenue stream may be years away; the government funding share helps enable this longer-term orientation. They began in the early 2000s and became a major financing mechanism by 2014, growing to help finance the "Made in China 2025" technology initiative issued in 2015.[13]

The fundraising target for these funds is up to $1.6 trillion, combining a market mechanism with national technology strategy. The amount raised by 2021 was estimated at around $1 trillion.

Each fund is sponsored by a national, provincial, or local government, which provides the initial funding, with additional funding coming from limited partners. Although state-sponsored, the funds take equity positions in companies and are managed by a general partner from the private sector. The funds are precluded from investing in real estate, secondary market stocks, derivatives, or futures—they are used for scale-up support.

Unlike past Chinese industrial support through mechanisms such as below-market debt, low-cost electricity, and direct grants, guidance funds focus on equity financing. But there can be subsidies involved: guidance funds can be, in effect, "below market equity" by enabling long-term commitments and lower returns to the government.

Typically, the Chinese government announces a target technology area for a fund, then seeds the effort with government patient capital.[14] This sends a signal to private-sector

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investors that an investment is safe, with the government sharing the risk. Those investors follow, becoming the limited partners.

Western commentators tend to decry guidance funds as very inefficient and a misallocation of resources from more productive investments, viewing their dual purpose—promote government industrial policy goals and allow a private-sector return, as inherently contradictory. There is, however, no getting around the reality of China's surge in the production of advanced technologies. For example, China began construction on twenty-nine new semiconductor fabs in 2021 and 2022;[15] the US, with the passage of the CHIPS Act, may build a handful of them. The key difference in achieving these numbers is the reality that government support for new fabs in China cuts the construction costs by 40 to 70 percent.[16]

China's advanced manufacturing institutes are another example. While the US, since 2012, has created sixteen of these, China has thirty and plans for forty by 2025.[17] Its institutes are from five to fifteen times the size of US institutes in terms of staff and funding. They don't simply offer grant programs to industry; they include major technology centers with in-house researchers, and are often physically surrounded by industrial companies focused on each institute's technology. China's institutes are much more like industrial research hubs than the US version. China also has an office with a staff of at least 100 studying every aspect of US manufacturing technology approaches. Meanwhile, the US has no such program to study manufacturing advances in China or other nations.

Bluntly, China's dominance in world manufacturing and its leadership in producing renewable energy technologies—solar, wind, and batteries,—is not a historical accident.[18] Since announcing its first electric vehicle (EV) subsidies in 2009, China has been engaged in an effort to dominate world EV production, and by 2015 it had become the leading EV producer.[19] Tesla's arrival in China in 2019 helped spur this effort, but in 2022, Tesla held only 10 percent of China's EV market.[20] In early 2023, China passed Japan and Germany as the world's largest exporter of passenger cars.[21] Governmental support has played a critical role in these efforts.

China faces its own deep challenges in terms of demographics, rising wages, regulatory uncertainties, corruption, wasted resources, and an increasingly repressive and erratic government. But a negative shift in China's growth model does not mean that the US will succeed in manufacturing. China's capability in rapid industrial scale-up is unsurpassed.

Therein lies the lesson. The US government has long driven investment into important economic sectors, from its subsidies to promote transcontinental railroads in the nineteenth century to the recent CHIPS Act subsidies for semiconductor production. But there is no systematic scale-up financing mechanism in the US, only occasional, scattershot approaches.

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The nature of the financing can also be complicated. For example, the amount of capital required for clean energy technologies such as renewable energy plants is high. While the lifetime cost of clean energy is now competitive with fossil fuels, renewable plants typically require considerably higher up-front investments despite their lower operating costs—which means that investors face longer wait times before they see returns. These kinds of problems often apply to hardtech investments in general, and they require attention not only to the availability of financing, but also to how it is structured to offset these problems. Markets are impatient by nature, but capital for clean and advanced manufacturing technologies must be patient and long term. China has employed such mechanisms.

Of course, we cannot simply replicate China's guidance funds; they are not a workable model in a US context. No American investor is going to be clamoring for "below market equity" approaches. However, it should be possible to design a financial investment model for longer-term scale-up of critical technologies and their production that still meets investor needs and encourages technology priorities.

If the US fills these two gaps—*cross-agency coordination* and *technology scale-up*—the nation could be well on its way to establishing the terrain on which to build an actual framework for industrial innovation. However, all the new approaches to industrial innovation policy discussed in chapter 12 face a challenge of gaining political and public support. When tried in the past, industrial policy approaches outside the defense arena, particularly energy technology demonstrations, have sometimes failed. Will they be effective and resilient enough to become politically accepted, with continuing policy support assured? And what other challenges need to be overcome?

GUIDING PRINCIPLES FOR A NEW INFRASTRUCTURE

There is another critical challenge: specific industrial innovation programs like the examples given in chapter 12 to illustrate the new approaches, because they operate at various innovation stages, are not enough. For an *overall* industrial innovation policy to work, it will require a larger framework—a new supporting infrastructure—built on a number of guiding organizational principles. Creating this new infrastructure will be a prerequisite for effective industrial innovation policy programs.

CREATE TEAMS OF CHANGE AGENTS

Innovation doesn't just happen; change agents are critical to complex innovation, as detailed in chapter 7.[22] Even if the elements of an innovation system are assembled, a

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catalyst or group of catalysts is needed to force the changes and connections that are needed, just as a conductor is required for an orchestra.

The team that created and led OWS is a good example of what the change agent role entails. Some of the characteristics of successful DARPA program managers also apply. For innovation programs to succeed, change agents need to be empowered with the authority to pursue their missions. They need visioning ability so they can see a new innovation territory. They need to be highly entrepreneurial and have "religion"—that is, dedication to their innovation task—about what they're working on. And they need to be effective collaborators who can work with and lead teams of other innovators.[23] These same characteristics must all be brought to industrial innovation policy projects in the form of a leadership *team*.

Other skill sets are needed too. Talented researchers will need to be involved, of course, but industrial innovation policy stretches beyond research. As the discussion of DOE demonstration projects in chapter 12 shows, expertise in project management, project engineering, and project finance will also be required. In addition, a knowledge of the bureaucracies involved and an understanding of their relevant legal and contracting authorities could prove vital, as OWS demonstrated. Understanding regional innovation could also be key because in the end, all innovation is local, not national—as projects called for in the CHIPS and Science Act illustrate.

The key point is that a new collection of skill sets is going to be required—a panoply of tech development, tech scale-up, tech financing, and tech production skills. Sticking traditionally trained scientists and engineers into leadership positions will not work; we may need to train change agents through new educational efforts. We do not have this talent base in place outside the DOD, and it must be built promptly.

CONNECT TO STRONG RESEARCH FOUNDATIONS

Industrial innovation policies focus on stages after initial research, but these policies are not only about application. The implementing programs that derive from these policies must also integrate with earlier-stage research. OWS was the beneficiary of vital research work on messenger ribonucleic acid (mRNA) and nanolipids that enabled rapid vaccine scale-up. Similarly, the applied technology advances called for in semiconductor advances, DOE demonstration programs, the CHIPS and Science Act, and the Inflation Reduction Act will all require extensive foundational research.

Ensuring connected research, with careful links and common agendas between basic and applied work, will be critical to ongoing and longer-term industrial innovation efforts.

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REBUILD MANUFACTURING FOUNDATIONS

A weakness of most of the industrial innovation policy-type programs discussed in chapter 12 is their lack of a manufacturing element. The decline in US manufacturing productivity—which has fallen since the late 2010s to historically low levels—and parallel declines in capital plant and equipment investments indicate that US adoption of advanced manufacturing technologies and processes is lagging its major competitors, which are doing better on productivity. Any industrial policy, however, is going to depend on a strong manufacturing system; absent a strong system, initiatives will tend to collapse like a house of cards in slow motion.

The US needs to see manufacturing as part of the innovation process, a view its leading industrial competitors have adopted. Even though many of the programs in chapter 12 that illustrate new industrial innovation policies focus on implementing advanced technologies, the US ran a massive and growing $244 billion deficit in advanced technology manufactured goods in 2022.[24]

Industrial innovation policies will often rely on advanced technologies and, if they are not manufactured in the US, the policies may be in jeopardy since overall innovation includes the manufacturing phase. This is an indicator that a number of pending industrial policy programs simply will not achieve their aims. It is also a signal that renewed focus on advanced manufacturing as a foundation for these programs will be critical if they are to work, although these programs, such as the advanced manufacturing institutes program, have received limited attention from the administrations of presidents Donald Trump and Joe Biden.

This is a critical gap that must be filled. Strengthening the manufacturing sector in general and implementing advanced manufacturing technologies and processes will be a critical foundation for industrial innovation policy programs; without this strengthened foundation, they will not work. The manufacturing policies needed include strengthening the funding for advanced manufacturing institutes; networking the institute efforts to they can produce packages of integrated technologies, such as three-dimensional printing that can sync with robots and digital production technologies, to speed adoption by companies; scale-up financing for advanced manufacturing equipment and facilities; workforce education programs for advanced manufacturing skills; and federal procurement programs, particularly at DOD, that require contractors to utilize advanced manufacturing approaches.[25]

MAP SUPPLY CHAINS AND FILL THE GAPS

There can be no gaps when building an innovation system through industrial policy approaches; strong connections are required throughout the system. Supply chains can

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be vital to an operational system, and it is by mapping those supply chains that gaps can be identified and filled.

Mapping supply chains was vital to the success of OWS. It is proving central to the effort to secure domestic supply chains for critical technologies and materials, and it clearly will be required in semiconductors, DOE technology demonstrations, the climate provisions in the Inflation Reduction Act, and the technologies called for in the CHIPS and Science Act.

TEST AND DEMONSTRATE TECHNOLOGIES

While many prototypes often evolve, only some ultimately will work well. Testing and demonstration are therefore critical innovation stages, as noted in chapter 12. The DOD, which has long followed industrial policy approaches, builds them into virtually all its technology development programs, but they are often missed in civilian agency efforts.

Testing and demonstration are also crucial to commercialization—firms and users will not be interested in a technology unless it is tested and proved. This is why developing testing and demonstration capability at DOE is so critical if new battery, advanced nuclear, and renewable technologies and processes for industrial decarbonization are to be developed and adopted.[26] This is the rationale for the DOE demonstration program and the new demonstration office created there to build the expertise to run it. Demonstration and testing will also be key to, and so are built into, the CHIPS and Science Act for the new technologies it will support.

INTEGRATE AGENCIES, INDUSTRY, AND UNIVERSITIES

All the innovation efforts reviewed in chapter 12 required, or will require, implementation in the private sector and full integration with industry efforts. None are solely for the government, as were the Manhattan Project and the *Apollo* project. This is the connection pathway that must be followed for semiconductors, the CHIPS and Science Act technologies, DOE demonstration projects, and secure domestic technology supply chain.

In OWS, integration between the government and private-sector vaccine makers reached a point where government personnel were located at a number of the firms involved to build understanding and speed up regulatory review. It is a good example of the importance for implementation success of industry partners being actively engaged and committed. If they are not, the projects will inevitably fail. Industry leadership is thus a significant aspect of successful industry engagement.

In programs that will move technologies from research through implementation, such as with semiconductor advances and the new technologies called for in the CHIPS and Science Act, integration between university research, government agencies, and industry

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will be required. Other projects will have important linkage aspects as well. All of these are complex collaborations that will require spelling out a host of operational rules.

CERTIFY AND VALIDATE TECHNOLOGIES

While the health sciences sector has a technology certification process—namely, the approval process of the US Food and Drug Administration (FDA)—that is fully accepted and recognized, no other sector has a similar mechanism. FDA approval amounts to a widely accepted technology validation system that guarantees immediate market acceptance, as discussed in chapters 8 and 12, making it a very powerful innovation tool. Indeed, it *commands* markets. As evidence, consider that even the technology certification of the FDA's *preliminary* step to full approval, Emergency Use Approval (EUA), proved vital to the success of OWS in limiting the effect of the pandemic, helping the adult population reach a fully vaccinated rate greater than 70 percent.

The utility of what the FDA does suggests that comparable technology certification or validation mechanisms should be considered as the government pursues industrial innovation policy approaches. The network of strong federal laboratories, for example, in cooperation with industry, might be able to play a role in this area comparable to the role that the Fraunhofer Institute labs play for German industry in technology validation.

ENSURE FINANCING

Initiatives for industrial innovation policy may grind to a halt unless financing is available for the technology projects required, as discussed previously with respect to technology scale-up. A variety of financing types may be appropriate for particular projects, including lending, guaranteed contracts, tax incentives, and procurement for initial market creation. Guaranteed contracts were crucial to the ability of OWS, for example, to scale up vaccine production rapidly. The DOE demonstration program relies on authority from the department's Loan Programs Office, as do the critical materials and minerals-development efforts called for in the initiative to secure critical domestic technologies and materials. The semiconductor initiative uses investment tax credits as well as loan guarantees as financing tools to enable domestic fab and foundry creation.

If advanced manufacturing is to be spurred as a foundational element for industrial policy initiatives, financing for new advanced manufacturing equipment, particularly at small and midsize manufacturers, will be needed, as noted previously. Recognizing this gap, a group of US senators introduced legislation in 2021 to create an Industrial Financing Corporation that would invest in innovative manufacturing.[27]

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Further, the Export Import Bank of the US, a government-owned financing bank to promote exports, could develop a domestic lending capability to meet domestic manufacturing requirements; it has some $80 billion in lending authority. This option was supported by the White House in 2022 to help secure critical supply chains.[28]

However it gets done, the importance of financing as a cornerstone of successful industrial innovation policy initiatives cannot be understated.

LEVERAGE ADVANCES THROUGH PROCUREMENT

Most of the mechanisms discussed here for implementing industrial innovation policy efforts operate on the supply side to promote technology development. But what about the demand side?

Government has an additional tool that can be applied to innovative new products and technologies: its large procurement programs.[29] If government, in addition to supporting technology development supporter, can act as an initial market creator—as it frequently does with new defense technologies—it can help assure scaling and acceptance of new technologies and systems.[30] Federal procurement and programs play a massive role in defense-related and health sectors; the accelerated OWS vaccine procurement effort is a good example.

The character of demand also shapes new industrial production processes, and the federal government can use its leverage over demand. For example, while defense production accounts for only a modest portion of total manufacturing output, a surprisingly sizable proportion of manufacturers rely on some defense contracts. Defense procurement can, therefore, leverage significant advances in production processes by requiring its contractor base to adopt advanced manufacturing technologies

Effective use of federal procurement can play a significant role in creating initial markets for new technologies in a number of areas. This could help shape the demand that will be key for new technologies to scale.

ESTABLISH FLEXIBLE CONTRACTING MECHANISMS

Flexible contracting mechanisms go hand in hand with procurement approaches. The Defense Production Act (DPA) provides authority for intervention into manufacturing supply chains to assure rapid production scale-up of critical goods related to national security. This authority proved critical to the success of OWS in rapidly developing and producing vaccines. Application of DPA authority is cited in the initiatives for DOE demonstrations and is used to secure critical technologies and materials.

There is also the Other Transactions Authority (OTA), developed initially by DARPA, to enable rapid contracting outside the cumbersome procedures of standard federal

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procurement; it has been applied by other agencies as well. These and other examples of flexible contracting authority may prove critical to industrial innovation policy approaches, as OWS indicates.

ASSESS NEW TECHNOLOGIES

Technology is an ever-changing picture. The US needs to establish a technology assessment capability that examines emerging technologies and updates its technology strategies based on developments. The CHIPS and Science Act of 2022 called for the OSTP to undertake a continuing technology strategy effort and established a Technology Innovation and Partnerships Directorate at NSF to assess and update a critical technologies list. A process for these critical technology assessments was proposed to NSF in 2023 by a group of leading academic experts.[31] A full technology assessment process is needed to closely examine where critical technologies are headed, review the opportunities, and adjust technology road maps and programs accordingly. Part of this needs to be an ongoing assessment of progress competitor nations are making on these technologies, as well as their accompanying industrial policies. And the new US industrial innovation policy programs themselves require objective and independent assessment.

SUMMING UP

Industrial innovation policy is a complex process with many actors, and it requires a careful plan, strong foundational programs, and a spirit of enterprise to accomplish it. As the Pentagon discovered long ago (and noted previously), you cannot just build the pieces—you must build the *system*.

To implement the new approaches to industrial innovation policy discussed in chapter 12, the US will need to adopt a "systems of innovation" approach. It means rethinking the linear pipeline model that has long dominated US views of technology organization. At the same time, it will need to approach innovation in a dynamic way, recognizing all its interdependent components, flows, organization, and underlying policies. It will need to address barriers and bottlenecks, with collaborating agencies brokering solutions; a scattered agency approach will not be enough. It will need scale-up support. And it will need a new infrastructure behind all this to sustain it. These operational mechanisms will be key to that new supporting infrastructure.

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14 CORE FINDINGS AND NEXT STEPS

Through the preceding chapters, this book has set forth a host of core concepts and essential ideas. As such, it should serve as a reference for developing science and technology policy, as well as industrial and industrial innovation policy. In addition, it has proposed steps for the US to take to strengthen and maintain its capabilities in these areas. This chapter provides a synopsis, reviewing these concepts and ideas.

DIRECT AND INDIRECT INNOVATION FACTORS

Economic growth theory provides a foundation for science and technology policy. As discussed in chapter 1, technological and related innovation drives some two-thirds of economic growth in this country, compelling the leading economist Robert Solow to develop a dynamic, innovation-based growth theory to explain US economic expansion in the twentieth century. Simply put, he was arguing that economies, to grow, must perform research and development (R&D).

Building on Solow, Paul Romer, another leading growth economist, argued that human capital employed in research was a second critical growth factor. In other words, the results from R&D efforts will only be as effective as the talent base behind them.

These two elements—*R&D* and the *talent base*—give us two direct innovation factors with which to assess the strength of any innovation system, national or regional.

An examination of the information technology (IT) transformation of the 1990s confirms the reality of technology-driven growth. Advances in semiconductors formed a core technology around which other applications—from personal computing to the internet—were added, creating a large enough effect to alter the economy. In turn, the large-scale productivity savings that this enabled increased the society's real wealth. It is

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a pattern seen again and again in innovation-based growth: a core technology enabling additional applications that drive productivity savings and grow the overall economy and societal well-being. This is the way it works.

Another economist, Richard Nelson, led us toward a third direct innovation factor: *innovation organization* (see chapter 2). Within national systems of innovation, which vary among nations, he found a mix of innovation actors operating—primarily companies, university research, and government labs. Companies are the most significant because they typically form the innovations from the underlying research. Drawing from Nelson's work, we find our third direct innovation factor: *innovation organization*.

It is not enough to have a science and technology talent base or use it to undertake R&D. A *system* that organizes innovation is also needed.

The strength of actors in such a system, and the connections between them, will be critical in determining the strength of an overall innovation system. Both government and the private sector play roles in the direct factors. For example, government in many nations plays a central role in supporting basic research, while industry supports the follow-on development. Through universities, government also funds much of science education, particularly at the graduate level, while industry employs the majority of scientists and engineers.

A fourth direct innovation factor, capacity in the *production and dissemination* of new technologies, is also essential (see chapter 9). The steps of manufacturing and introducing a technology at scale so that it becomes widespread teach crucial and creative lessons that greatly alter the prototype. Without these, an innovation would be stuck at the prototype stage, an invention not a true innovation.

Beyond these four direct factors, innovation is an even more complex system, though, with many *indirect* factors interacting with the direct ones. While not as crucial to innovation as the direct factors, the indirect factors are still significant. Some of these, such as investment capital, markets, management and management organization, and talent compensation, are under private-sector control; others are driven or affected by government policies, including fiscal and tax policy, trade policy, intellectual property protection, regulatory policies, financial standards, and so on. Figure 2.1 in chapter 2 diagrams these direct and indirect innovation factors.

GOVERNMENTS AND THEIR ROLE

Striking the right balance between government and industry roles has been the subject of long and continuing debate over industrial policy. Mainstream economists, while

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acknowledging market failures in the ability of industry to support basic research and science education, have long cautioned against government intrusion into decisions that economic efficiency dictates should be made by those markets. These economists of the dominant neoclassical school typically assume perfect competition, with firms selling the same products and competing over price.

A more dynamic theory of growth, argues the Cambridge University chancellor David Sainsbury, finds that firms compete by trying to gain competitive advantage with new products or product improvements (see chapter 2). Products aren't the same; they are constantly changing, with firms seeking high levels of value added and nations building wealth when their firms are successful in producing high value-adds per capita.

This dynamic capability of firms, then, becomes crucial, extending the direct innovation organization factor. The government role is more complex than one of simply respecting markets; government needs to become involved more strategically to ensure that there are both the foundations and needed elements for firms to exercise this dynamic capacity, including through public-private partnerships.

DISCONNECTED AMERICAN INNOVATION ORGANIZATION

A number of political ideologies have evolved in the US around technological innovation (see chapter 3):

- *Associationalism* calls for public- and private-sector R&D collaborations.
- *Conservatism* supports federal R&D only for specific national security needs.
- *Reform liberalism* argues that competition spurs innovation, supports antitrust efforts, and opposes collusion by large firms.
- A *Keynesian strand* backs overall government investment in R&D to reduce market failures.
- *A national security strand* presses for defense-related economic interventions, regardless of how economically intrusive, to meet national security needs.

These ideological perspectives, as David Hart has pointed out, had become locked in by the 1930s and continue to dominate political debate over the federal role in innovation. Two decades into the twenty-first century, *associationalism* and *national security* are perhaps the most powerful.

The national security perspective, employing large-scale public-private collaborations, certainly led to government's dramatic role in spurring technology innovation during World War II, and later during the Cold War as well. However, President

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Franklin D. Roosevelt's wartime science adviser, Vannevar Bush, was concerned that the remarkable R&D operation that he helped to build would disappear in postwar budget cuts. Therefore, he advocated a federally funded science agency that would support basic research at universities, leaving the follow-on steps to industry. He was proposing what came to be known as the "pipeline model" of innovation, in which the government inserted basic research (performed at federally funded research universities, which had scaled up during the war) into one end of the innovation pipeline, and then industry provided all the other inputs so major technology advances could emerge.

This model prevailed in the postwar period for the many decentralized, nondefense R&D agencies that were created or evolved over time. Bush's push for a science agency became the National Science Foundation (NSF), devoted to basic research. But these agencies were typically tied to larger mission-based government organizations, such as what became the US Department of Health and Human Services (HHS)'s National Institutes of Health (NIH) and the US Department of Energy (DOE)'s Office of Science.

The decentralized and disconnected nature of US R&D support has made science initiatives that require cross-agency collaborations—such as for nanotechnology—very difficult to organize. This disconnected approach did not encourage "use-inspired science," where scientists would pursue a needed outcome, going back to the basic research to get there and yielding both basic and applied results. It came under growing attack in the 1970s and 1980s as the US continued to invent new technologies (aided by its strong basic research system) but failed to bring them to market. The importance of applied science and engineering (S&E) and of strong links between industry and the basic research system was missed. In effect, these problems were designed into its system by the Bush model of government support for basic research, leaving the follow-on steps to industry. The disconnect led to the major focus of science and technology policy since the 1990s: building bridging mechanisms across the so-called valley of death—the yawning gap between R&D in the US.

In essence, the US had built parallel universes: one with a connected defense innovation system with extensive government-industry-university collaborations justified by a national security rationale (discussed in chapter 4), and another with a decentralized civilian agency R&D system. In the former, defense funding supported R&D, prototyping, testing, demonstrations, and the introduction of initial technologies—and it has led to most of the major innovation waves since the 1950s (aviation advances, nuclear power, electronics, space, computing, and the internet). The latter was busy pursuing basic research, disconnected from industry, to feed one end of the pipeline model.

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THE ROLE OF PEOPLE IN INNOVATION

Innovation may take place at the institutional level, but people, not institutions, do the actual innovating. And while discovery and invention can be individual endeavors, the more complex process of innovation involves a range of technical fields and expertise, so it requires *groups* of people (as reviewed in chapter 5).

Examining a host of teams—Thomas Edison's group in Menlo Park, New Jersey; the Manhattan Project; Xerox PARC; the beginnings of biotech; mapping the human genome; and others—reveals certain characteristics that "great groups" tend to share (see chapter 5). These include creating a mass of superb talent; a dynamic relationship between the group and its strong leaders; deep collaboration within the group, with members contributing different skills; protecting the group from bureaucrats on an "island," but with a solid "bridge" back to supportive decision-makers; wearing blinders so the group is always focused on the project; and knowing that the project has to come to a conclusion and ship the technology into implementation.

Every outstanding innovation group is different. The groups often develop their own approaches, but most exhibit many of these characteristics. They all must strike a critical balance between the role that group leaders play in identifying team talent, setting the structure and communication and finding the equipment, and the collaboration that needs to prevail among the group.

These characteristics become a set of principles to follow in creating a great innovation team. They stand as a reminder that the pursuit of innovation is an intensely human activity, full of great stories of people and what they can accomplish together.

THE DARPA MODEL

The Defense Advanced Research Projects Agency (DARPA) is central to the story of US science and technology policy. It uniquely combines a highly innovative institutional model for innovation with what we have learned about the importance of a great group.

DARPA has been tremendously effective in fostering numerous groups of great innovators. The ability to innovate at both the organization and personal/team levels has been key to DARPA's success (as detailed in chapter 6). The agency has to live with failures in order to gain successes but, on a good day, it helps form and support great groups of innovators.

DARPA is small and flexible, nonhierarchical, and entrepreneurial. It has no lab of its own; instead, it identifies and works with outstanding researcher groups elsewhere,

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applying a hybrid model that brings together academic and industry researchers—particularly from smaller firms and start-ups. It focuses on technology challenges and corresponding breakthroughs that will have significant impact, not on incremental advances.

Routinely, DARPA takes risks to achieve revolutionary technologies. It does not employ the inherently more cautious peer review committee approach, but it is led by empowered program managers with significant autonomy and three- to five-year terms in which to move their technology ideas into prototypes. It accepts risks and failures.

There are other characteristics as well. DARPA follows the island/bridge approach: it is on an island, isolated from the military bureaucracy, but it has a solid bridge back to key US Department of Defense (DOD) decision-makers, particularly in the secretary's office, who can push its advances. In the fields where it works, it builds thinking communities of thought leaders that can be a source of ideas, as well as supporters for implementing the new technologies being pursued. DARPA also links the technologists that it is backing with operators who will use the technology, so the technology can be practical and developed to serve real needs.

DARPA's success is best exemplified by the IT revolution, which it played a significant role in fostering. In that and other cases, DARPA went beyond the "use-inspired" research concept mentioned earlier to foster the prototypes that introduced significant innovations. The agency became a bridging mechanism not simply between R&D, but also technology implementation. It added another dimension to the innovation pipeline, pushing past the development stage into the introduction of new technologies—thus establishing the "extended pipeline model." Although it relied largely on the private sector to scale its advances in personal computing, in other areas, it often used the DOD procurement budget.

The DARPA model was subsequently applied successfully to the energy technology sector through the Advanced Research Projects Agency–Energy (ARPA-E) and, through the Intelligence Advanced Research Projects Agency (IARPA) for information-related technologies for the intelligence sector. In 2022, the Advanced Research Projects Agency for Health (ARPA-Health) was funded and formed, and several nations have attempted to emulate the model. DARPA offers an organizational model that appears to have wider application beyond the defense sector.

THE LEGACY-SECTOR CHALLENGE

The US has a dual innovation structure, part suited to innovation and part resistant to change. Only a small portion of economies consist of innovative new sectors, and the

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US economy is dominated by complex, established legacy sectors. Even where the valley of death between research and later-stage development can be crossed, if the innovation is set to land in one of those legacy sectors, it faces challenges to subsequent implementation.

Legacy sectors form a technological, economic, political, and social paradigm that operates like a moat around their castles, protecting their established technologies and blocking threats from new-entrant technologies. As set out in chapter 7, the barriers include perverse subsidies, protective institutional architecture and infrastructure, and market imperfections that disadvantage other technologies. Politically powerful vested interests, a financing system that benefits existing technologies, public habits and a cost structure that favor current technologies, an established knowledge base that helps incumbent technologies, and a general aversion to innovation that limits support for new technologies are additional barriers.

New innovations thus are most likely to scale up in open territory absent opposition from legacy-sector technologies. The innovation that spawned the computer revolution essentially created its own new territory—there was nothing quite like computing before computing showed up. The US finds it very difficult to innovate in its long-established healthcare delivery sector, but biotechs have thrived because they found a relatively open field. Technologies landing in legacy sectors have to parachute into occupied territory, often facing "enemy fire" on the way down, so to speak. In the legacy energy sector, for instance, the fossil fuel paradigm is doing the shooting (see chapter 10).

The US can do a better job of bringing innovation into legacy economic sectors with a *unified approach* that integrates four longstanding models into a fifth model built around innovation organization (as detailed in chapter 7):

- *Pipeline model*: Supporting early-stage research in the expectation and hope that the private sector will pick it up and transform it into new technologies
- *Induced innovation*: Innovating largely through incremental advances, as industry does, rather than through radical advances—a demand-driven model through which industry identifies a market opportunity and then nurtures a technology to fit it
- *Extended pipeline*: Supporting research and extending support down the pipeline through the development, prototype, testing, demonstration, and product design stages, as the DOD does
- *Manufacturing-led*: Focusing the innovation system on new manufacturing technologies and processes as in Japan, Germany, South Korea, Taiwan, and China, rather than on R&D, as the US has done

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- *Innovation organization*: Unifying all these models together in a new organization that can foster whatever is needed to advance and succeed, as a complex, diverse economy demands

This *unified approach* is key to overcoming the barriers of complex legacy sectors.

Getting there will require a number of steps, beginning with identifying the gaps in an innovation system that need to be filled, and also including the following:

- *Identifying possible launch paths for the entry of new technologies*, which will be different for experimental, disruptive, and secondary (component) technologies; making manufacturing system improvements, for example, can be part of this process.
- *Developing supportive governmental policies*, from "carrots"—subsidies and tax benefits—to "sticks"—regulatory mandates; these amount to a mix of front-end technology support at the R&D, prototyping, and other stages up to production, as well as back-end incentives and sticks for technology scale-up.

This is a rough sketch of the kind of innovation system thinking and approach needed to overcome the legacy-sector barriers to new technologies.

CHALLENGES IN THREE SECTORS: LIFE SCIENCES, MANUFACTURING, AND ENERGY

Innovation isn't uniform; it varies from sector to sector and thus requires analysis addressing each sector. The three sectors explored in some detail (in chapters 8, 9, and 10, respectively) reinforce the analysis presented in the preceding chapters and summarized in this chapter, while also demonstrating the opportunities for doing things differently—employing the *unified approach* to innovation in particular.

Each sector is briefly summarized next.

LIFE SCIENCES

The US life sciences sector is one in which tremendous successes are coupled with huge challenges to developing and disseminating the next generation of medical advances. Overall, healthcare is a legacy sector, with established technologies, institutions, and systems that are very difficult to change. The full details can be found in chapter 7.

The NIH, by far the best-funded R&D program in the US (dwarfing other such agencies),[1] sits at the center of the sector. NIH has played a huge role in one of the direct innovation factors (see chapter 1) by training a major army of researchers because its research supports mentor-based education at the graduate level. This investment and talent base have, in turn, fed and staffed the innovators who have, through start-ups, pursued medical advances and created the biotech industry—one of the most important

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innovation system developments in the US. And the biotechs have been able to obtain long-term risk capital from venture capitalists.

VCs are able to manage these risks because the federal drug regulator, the FDA, has created a risk benchmarking system through its three-phase drug approval process and final approval process, which amounts to a nearly universally recognized drug certification assuring immediate market acceptance. No other innovation sector has been able to obtain such long-term risk capital. The development of biotechs also largely erased the "upstairs/downstairs" relationship between industry and academia—researchers can now move relatively easily between the two, improving the opportunity for implementing medical advances.

That positive history, though, has not overcome deep innovation organization problems at NIH. Its diffuse structure of institutes and centers organized around various diseases makes it very difficult to adopt new, cross-cutting research approaches; collaboration across its many stovepipes is very hard to achieve as well. Organized around a biology-only approach, NIH lacks engineers and computational scientists despite the widespread view that many emerging medical advances will come from the convergence of these fields. The peer review system tends to be inherently conservative, avoiding higher-risk, breakthrough research and focusing instead on incremental advances. NIH research support also tends to be scattered across many small projects. As Susan Hockfield, the former president of the Massachusetts Institute of Technology (MIT), once commented, its approach is to let 1,000 flowers bloom, but sometimes it's important to assemble a garden.

NIH's grant structure makes gardening difficult. The political environment that fuels its strong funding but reinforces this decentralized structure is not going to change anytime soon. NIH's peer review system tends to move slowly on its grant awards and focuses on incremental advances while avoiding higher-risk, breakthrough research. For these and other reasons, the Biden administration and Congress in 2022 created a DARPA-like model for health research, ARPA-Health, to pursue innovative health research pathways in ways that NIH hasn't been able to do.[2]

Beyond the NIH organizational challenge to the health innovation system, there are issues at the FDA. While not an R&D agency, it needs to be able to develop and apply new science advances to speed up and improve its regulatory processes in the face of the soaring costs of its approval process. That creates a market imperfection for medical advances and compels firms to focus development on blockbuster drugs that command large markets, rather than on remedies that serve small-population and developing-world diseases.

Another problem, seen clearly during the COVID-19 pandemic in 2020 and 2021, was that the offshoring of so much production of US pharmaceuticals and medical

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goods had created critical, life-threatening shortages. Innovation and production are closely tied.

There are, however, some positive signals emerging from the life sciences sector. ARPA-H was formed as a new innovation organization that could fill some of the gaps in the current innovation system. Despite barriers put up by NIH, there is a new convergence-based approach is evolving for medical research, which adds engineering, computation, and physical sciences to biology to spur new kinds of life sciences innovation. Several major universities have now formed convergence-based research organizations within their research mix, and NIH itself has sponsored efforts to support more high-risk research and awards to younger researchers so their ideas get support earlier in their careers.

In addition, Operation Warp Speed (OWS) was formed in 2020 to confront the coronavirus pandemic and succeeded in developing and distributing highly effective vaccines, including breakthrough messenger ribonucleic acid (mRNA) vaccines, not in a decade but in *eight months*—an amazing organizational development that saved many millions of lives. The many mechanisms that OWS employed to accelerate innovation (discussed in detail in chapter 8)—a portfolio approach to vaccine technologies, guaranteed contracts, faster clinical trials, and cross-agency collaboration, among others—spurred this success and offer many lessons. OWS filled all the innovation system gaps that its mission confronted, and its elements are potentially applicable to other life sciences challenges and to other sectors of the economy.

ADVANCED MANUFACTURING

The US was the first nation to master the manufacturing innovation wave around mass production technologies and processes. Chapter 9 describes this history, including how, by the early twentieth century, the US—buttressed by its massive internal common market—had applied these technologies to become the world's leading industrial economy. The systematic industrial policies of World War II that scaled up its production capacity multiplied that dominance by the immediate postwar period—growing into a lead that was so large that manufacturing was an afterthought as the country's postwar R&D system was designed. The US R&D system focused on basic research and defense technology development, while postwar Germany and Japan focused on manufacturing-led innovation.

In fact, it was Japan—not the US—that led the next big manufacturing innovation wave in the 1970s and 1980s, which involved quality production. The US played catch-up on quality for years thereafter. Japan became the leader in the automotive and consumer electronics industries, and the US got its Rust Belt. As detailed in chapter 9, Germany developed the world's strongest manufacturing workforce education system

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to improve its productivity, and the US did nothing even comparable. And then China emerged, with a manufacturing economy that coupled low wages with an ability to scale up production volume rapidly and redesign products to reduce production costs.

US manufacturing jobs declined significantly as China assumed world manufacturing dominance. Meanwhile, Germany, South Korea, Taiwan, and Japan established advanced, high-cost, high-wage manufacturing economies by taking advantage of manufacturing-led innovations. China has since been following their examples by implementing its own manufacturing-led innovation. The US failure to compete effectively in manufacturing led to a long period of rising income inequality, a working class frustrated socially and economically, and the political instability that had been building up to the results of the 2016 presidential election.

Other nations are now moving to adopt advanced manufacturing to give themselves a competitive productivity-based advantage. The idea is that a new wave of digital and other advances will enable new production technologies and processes to jump-start efficiency over competitors. The US, though, in the face of manufacturing productivity that remains historically low, continues to move only slowly to adopt what appears key to retaining an industrial economy in this country.

The US could compete by using its still-strong innovation system to adopt advanced manufacturing.[3] The Manufacturing Innovation Institutes that began in 2012 are a public-private partnership model that points toward one way forward, bringing together regional manufacturers with federal seed funding, university engineering and science, and state and local government support. But the *weaknesses in the manufacturing institute program* need correction. The small and midsize manufacturers that provide close to half of US manufacturing output, but also have the worst productivity problems, need this program the most. But five-year term limits for federal funding forced the institutes to turn to their large company members for funding for survival; this meant dropping programs for smaller firms. The five-year term limits need to end—a shift that two of the three federal agencies that support the institutes, the US Commerce Department and the DOD, began to make in 2021.

This program also needs *cross-institute networking capability* so that promising new technologies from the institutes can become adoptable *packages*. Firms don't want to adopt a *single* manufacturing technology process; they want *packages* of robotics, digital production, *and* advanced materials. And firms want workers skilled in these areas, too, so while *workforce education* is a key institute role, that underfunding needs correction, and efforts need to be networked, not scattered.

Beyond fixing the institute model, the US must fill a *major gap in scale-up financing* for manufacturing. China spends some $450 billion per year to bring its companies into

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large-scale production. Its guidance funds, described in chapter 13, offer $1 trillion in financing (as of 2021) for scale-up through equity funding, with government funding matched by private-sector funding for projects selected by private-sector managers. The government prioritizes hardtech support. The US needs some comparable vehicle, some new financing mechanisms, given that the country's venture capital (VC) system is risk-averse to hardtech funding. It is a gap in the US innovation system that must be filled.

A third element requires *building manufacturing R&D within US R&D agencies*. This research agenda is largely missing at the R&D agencies, so the manufacturing institutes are not connected to the federal R&D system. A new R&D agenda in the agencies at earlier as well as applied stages is needed to keep renewing the manufacturing technology pipeline with new innovation.

Further, there is *federal procurement*, which could be used to foster the implementation of advanced manufacturing technologies. Back in the 1960s, the DOD mandated computer numerically controlled (CNC) equipment for its manufacturing contractors because it needed CNC precision for its missile programs. This spread CNC equipment throughout industry as well. A creative effort to use DOD and other agency procurement requirements could play a role in adopting advanced manufacturing technologies. Other steps include mapping supply chains for critical technologies and filling the gaps, bringing together groups of employers for collaboration with community colleges and state and local governments in workforce development, and creating a White House Office to oversee efforts across the involved agencies.

The production system is closely tied to the strength of the innovation system. Initial production is highly innovative, and moving to the production of advanced technologies requires extensive engineering, and often also rethinking the initial science that goes into innovation. Missing that production innovation stage significantly weakens an innovation system, which constitutes a major risk to continued overall US economic security. As noted already, capability in the production and dissemination of new technologies amounts to a fourth direct innovation factor, which is key to the ability to innovate.

A US economy that "innovates here but produces there" risks offshoring innovating as well as producing. The US needs both R&D-based innovation and manufacturing-led innovation to retain a strong innovation system and corresponding innovation-based growth. This is a central finding of this book.

ENERGY TECHNOLOGY

Innovating in the energy sector is even more complex than in the life sciences and advanced manufacturing, and the challenges are more massive. The problem of scale

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looms over every initiative, as noted in chapter 10. Shifting from fossil fuels is a tremendous undertaking in scale and scope.

The "wedges" theory formulated in 2004 has become the underlying approach for combating climate change (see chapter 10).[4] No single technology will work; a mix of new energy technologies and conservation practices is required, each of which can scale gradually, with a number becoming large enough to stabilize carbon emissions and ultimately achieve the much deeper emissions cuts that we now know (compared to 2004) are needed.

How will this be achieved? Many of the requirements are clear. New technologies will need to be *private-sector led* to ensure that they enter commercial terrain. Approaches must be *technology neutral* so we don't lock in to inadequate technologies too early. The effort will also have to be *organized around the obstacles to launching new technology into energy markets* to overcome the network of barriers that it will face. This all points to an unavoidable conclusion: we must adopt the new, *unified approach* to innovation described in this chapter and detailed in chapter 7 in the discussion of innovation in legacy sectors such as energy—the most challenging of such sectors.

If a unified innovation approach is needed, what steps will need to be followed for launching new energy technologies? Because energy is a legacy sector, the points noted in chapter 7 again apply:

- Identify the relevant market launch paths. Each technology launch will be somewhat different, but there are essentially four basic categories where most will fit. *Experimental technologies* such as fusion require an extended period to scale, but since the climate challenge is multidecadal, they will still be needed. Shorter-term, *potentially disruptive innovation that can scale in niche markets*, such as light-emitting diode (LED) lighting, will be needed. *Secondary innovations that face uncontested launch*—typically component innovations that are part of larger systems, such as batteries for electric vehicles (EVs)—will be necessary; firms in control of the larger system (e.g., automobiles) will accept them, provided they can compete on costs. But *secondary innovations that face contested launch*—where firms in control of the system will oppose their introduction, such as utilities facing carbon capture and sequestration—will require regulatory mandates.
- Tie policy packages to the applicable technology launch paths. Nearly all emerging energy technology technologies can use *front-end support* in the form of federal support for research and preproduction development stages. Many emerging technologies will also need *back-end incentives*—at the production and implementation stages—to emerge at a scale where they can become wedges that will make a difference. This

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means applying government-backed incentives, "carrots," particularly for secondary innovations that face an uncontested launch; and back-end regulatory mandates, "sticks," which will be needed for secondary technologies that face a contested launch.

Two more steps are required to bring all this about.

- Analyze the innovation system to identify gaps in the system. In the energy sector, for example, there is a major gap for scale-up financing to bring new technologies into production at sufficient scale. Technologies such as carbon capture and sequestration, hydrogen fuels, renewal of the grid, and advanced nuclear capability will take hundreds of billions in investment to implement—private-sector financing will need to be incentivized to meet these needs.
- Fill those gaps. There are already examples of this that we can point to, such as expanding the DOE's loan financing program and the creation of ARPA-E as a DARPA-like model for energy. The National Academies and Congress identified a gap in the energy innovation system in late-stage development and prototyping for new energy technologies, so ARPA-E was put in place to fill that gap.

Environmentalists and economists in the US in the 1980s identified a basic approach to tackle climate change: putting a price on carbon emissions through a cap-and-trade system. The idea was straightforward—limit the level of carbon emissions by raising their price and creating an opening for new technologies to emerge at competitive prices. This strategy, based around neoclassical economic tools of pricing and markets, would be introduced throughout the entire economy. This economywide pricing system has proved too much for the political system to absorb; at this time, a strong-enough political consensus around climate change to implement this "stick" has yet to emerge.

A pricing system misses many of complexities of the innovation system needed for developing the new energy technologies. Instead of cap and trade, the US has gradually been adopting a technology development strategy, unconsciously applying many of the steps identified here. While a carbon pricing system may well still be needed, significant progress can be made through an energy technology development strategy.

Other problems, though, have emerged in this process. When a leading technology approach emerges and dominates a sector, this *dominant design* locks in. That can preclude alternative and potentially optimal technologies from emerging, creating a problem of *stranded innovation*. The solar industry provides an example: it is dominated by relatively inefficient solar photovoltaic panels, despite the fact that thin-film solar technologies may be more efficient. The lock-in phenomena is making thin film a stranded innovation without available pathways to scale up.

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The solution lies in technology-neutral policies that allow improved energy technologies to emerge; such policies will be important in addressing climate change.

WORKFORCE EDUCATION

This discussion of core concepts and next steps has focused on the problems behind the first, third, and fourth direct innovation factors identified in chapters 1 through 3 and in chapter 9: building strong R&D, forming an overall innovation system, and supporting production and diffusion capacities. But the second direct innovation factor—the talent base for science and technology innovation—is a key element that cannot be ignored.

This talent base, as discussed in chapter 11, includes both the professional science and technical workforces—and the US is simply not generating the numbers of workers and the sorts of skills needed in either category. The failure to deal with what is a *workforce education* problem has also meant missing an opportunity to address the nation's income inequality and corresponding social disruption issues. While wage equality was mitigated by tightened post-COVID labor markets, a major gap remains.

"Human capital employed in research" is a direct innovation factor, as the economist Paul Romer has argued, and the number of scientists and technologists in the innovation system has a direct effect on the level of innovation. Concerning science, though, the economic signals in the US education system aren't working. As reviewed in chapter 10, the federal tax system subsidizes corporate R&D, although greater incentives for talent education could have a more direct impact. And universities have created *disincentives* for completing S&E degrees. Adjustments to the talent incentive system are required.

The skilled technical workforce, which often lacks college degrees, has not been seen as crucial to technological advancement and growth. Along with scientists and engineers, this technical workforce is a vital element in the overall technical talent pool, but the US has never established a workforce education system equal to the task. Nevertheless, the level of technical skills required to operate an increasingly complex, technology-oriented economy keeps growing. For example, a workforce education system that addresses the IT skills now needed in nearly every economic sector is largely missing.

Improving the skills of the technical workforce to meet the needs of employers who offer quality jobs should be a top education priority. Change is needed at all levels. Community colleges need to introduce programs and curricula in advancing fields, create short programs better adapted to upskilling workers already in the workforce, establish certificates around particular skills that stack toward degrees, and turn around low completion rates. At the federal level, Labor Department programs need to reach incumbent workers and

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teach advanced as well as basic skills; Education Department programs need to emphasize workforce education, not just college education; and both departments need to integrate their disconnected programs and expand apprenticeship programs. At the industry level, firms must collaborate with each other and with community colleges to build new training and apprenticeship programs, including youth apprenticeships starting in high school. Universities have been disengaged in workforce challenges, but lifelong learning programs are needed to update people's skills. State and local governments need to improve community college funding and support, integrate advanced programs in advanced technologies across community colleges with employers, promote apprenticeships, and work closely with area firms on reforms and curricula.

As detailed in chapter 11, *building a strong technical workforce education system* requires short technical courses that are stackable and lead to both degrees and industry-recognized certificates; programs at community colleges that reach not only community college students, but also high school students and incumbent workers; apprenticeships including youth apprenticeships that combine on-the-job learning with technical education; new online and other education technologies that will enable the scaling-up of workforce programs; improving community college completion rates; new curricula that can train for advanced skills in emerging areas; connecting historically separate Labor and Education Department programs so that they become complementary and reach incumbent and new entrant workers for new skills; universities that embrace their potential roles in workforce education rather than just assume that it's someone else's job; an expanded employer role in supporting curricula, apprenticeships, and new skill standards; and a much better workforce information system for employers, workers, and educators for inefficient and decentralized labor markets. It's a tall order but a crucial one, since workforce education is an essential part of the innovation system.

AMERICA'S NEW INDUSTRIAL INNOVATION POLICY

Science and technology policies are fundamental not only to our economic well-being but to climate, health, and economic security challenges. Because technologies are also a double-edged sword—they can be central to progress, but they almost invariably have both beneficial and harmful aspects—they require these policies to manage the R&D that go into them, how they are implemented and diffused, and ultimately their use. Artificial intelligence (AI) is the latest chapter in this long story.

There has been a longstanding tension, identified throughout this book, over the US government's role in science and technology policy. Over the decades, this role has veered between intervention and noninterference, with war and competitive crises

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driving greater involvement. In the postwar and Cold War periods, dualism prevailed: the DOD adopted active industrial policies under a national security banner, while the rest of the economy generally avoided such interventions.

Broadly defined, "industrial policy" has typically referred to government policies that alter economic policy toward industrial sectors and technologies. Between 2020 and 2022, the situation just described changed and a set of highly interventionist approaches emerged (as detailed in chapter 12), driven by the global coronavirus pandemic, increasing security tensions with China, and growing concern about climate change. The policies included large-scale energy demonstration programs, a massive incentive program to support the adoption of new energy technologies, programs to improve supply chain resilience, support for new semiconductor fabs and research, and adding an applied directorate to NSF's long-established basic research program. Economic security and related concerns tended to override the decades-long opposition of mainstream economists who focus on market efficiencies and pricing.

These newly emerged approaches policies are better labeled *industrial innovation policy*. Focused on the governmental role in fostering innovation, this policy is found in new programs that have broadened the governmental role beyond research to include support for later innovation stages, from prototyping to production. The US has been building up to these approaches for a long time, beginning its defense innovation support during the Cold War and continuing with competitiveness policies in response to Japan's development of quality manufacturing, development of new energy technologies, and efforts to encourage advanced manufacturing.

Marking a significant policy turn toward industrial innovation policies, these ambitious new approaches and the programs that exemplify them go further—even if major gaps in the innovation system remain, as discussed earlier in this chapter and throughout the rest of this work. The new approaches called for in the 2020–2022 programs included top-down programs for particular firms to advance new technologies, bottom-up efforts to broadly incentivize new technology adoption, technology demonstration programs, direct support for advanced production facilities, supporting more resilient supply chains, coupling basic and applied research programs, and regional implementation centers.

But, as discussed in chapter 13, a new infrastructure to support this complex mix of industrial innovation policies needs to be formed if they are to be successful. This new infrastructure includes cross-agency coordination mechanisms; financing for technology scale-up; a new focus on advanced manufacturing efficiencies; creating change agents skilled in project management, not just research; linking applied to basic research foundations; mapping and filling supply chain gaps; testing and demonstrating

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technologies; better integration of agency, industry, and university efforts; technology certification; using federal procurement to implement advances; and a new assessment system for emerging technologies and competitor capabilities.

Helping us understand the full scope of science and technology policy, industrial policy, and the new industrial innovation policy approaches and their implications—both in general and with many detailed examples—has been this book's purpose. Many nations recognize and follow science and technology policies more consciously than do US policymakers. Most Americans are largely ignorant of these policies and their importance to their everyday lives. We cannot afford to fly blindly into the future.

Science and technology policies—embodied in these new industrial innovation policy approaches—have a crucial role to play in meeting our most complex challenges.

To meet the challenge of climate change, and to create the kind of high-quality work to which our population aspires, call for a massive technological shift. Pursuing R&D and hoping for the best is not a sufficient strategy for the future. We need to treat this as a societal change. We must understand the entire, rich production process as being central to the innovation systems that drive societal change. We need to remake industrial processes to create workplaces where the workforce can thrive and where society as a whole can attain the economic security vital to our future and that of others—and do so entirely outside of fossil fuels.

Europe led the first Industrial Revolution and the century of both progress and disruption that it created. Today, we need a new kind of industrial revolution oriented around the dramatic new technologies required to transform our natural, economic, and workplace environments. This revolution must be designed to *serve*, not disrupt society—so we must think very big.

New science, technology, and innovation policies must be the beating heart of this task.

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NOTES

INTRODUCTION

1. Rotman, "Nicholas Stern (interview)."

2. Tooze, *Shutdown*, 34, 44–48.

3. Hightower, *There's Nothing in the Middle of the Road But Yellow Stripes and Dead Armadillos*.

4. Autor, Dorn, and Hanson, "The China Shock"; Autor, Dorn, and Hanson, *On the Persistence of the China Shock*.

5. Bonvillian and Sarma, *Workforce Education*.

CHAPTER 1

1. This summary of Solow's theory is drawn from his own description of his work in his Nobel Prize lecture of 1987. See Solow, "Growth Theory and After," which is the source for all the quotes from Solow herein.

2. See Harrod, *An Essay in Dynamic Theory*, and work by Domar, "An Essay in Dynamic Theory."

3. Solow was not the only neoclassical growth theorist. In 1956, for example, both Solow and Trevor Swan were working independently on forming neoclassical growth theory. The next year, Solow added technological change into the model. They are jointly credited with what is known as the "Solow-Swann growth model."

4. Denison, *Trends in American Economic Growth*.

5. Dosi et al., "Embodied and Disembodied Technological Change."

6. Solow, *Building a Science of Economics for the Real World*.

7. Frost, *North of Boston*.

8. Romer, "The Trouble with Macroeconomics." See also Romer, "Mathiness in the Theory of Economic Growth," in which he writes, "Mathiness lets academic politics masquerade as science."

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9. See, for example, Romer, "The Dismal Kingdom"; and Romer, "What Went Wrong."

10. *The Economist*, "Paul Romer Quits After an Embarrassing Row."

11. Romer, "Endogenous Technological Change."

12. The story behind the development of Romer's ideas is set out in Warsh, *Knowledge and the Wealth of Nations*.

13. Jones, "Paul Romer."

14. Romer, "Endogenous Technological Change," 71, 72.

15. The *Oslo Manual* is a respected source for data on innovation activities in industry, including understanding the innovation process. See Organisation for Economic Cooperation and Development (OECD), *Oslo Manual 2018*.

16. Romer, "Endogenous Technological Change," 72.

17. Romer, "Endogenous Technological Change," 73–75.

18. OECD, *Oslo Manual 2018*, 83.

19. Cf. Autor, "Trade and Labor Markets," 431.

20. Jorgenson, "U.S. Economic Growth in the Information Age."

21. Intel data here cited in Atkinson, *The Past and Future of America's Economy*, 98–99.

22. Atkinson, *The Past and Future of America's Economy*, 98–99.

23. Jorgenson, "U.S. Economic Growth in the Information Age."

24. Mulunovich and Roy, "The Next Small Thing."

25. Feynman, "There's Plenty of Room at the Bottom."

26. Drexler, "Molecular Engineering." See also Drexler, *Engines of Creation*.

27. Mulunovich and Roy, "The Next Small Thing," 2.

28. Mulunovich and Roy, "The Next Small Thing," 5.

29. Mulunovich and Roy, "The Next Small Thing," 1–2.

30. Mulunovich and Roy, "The Next Small Thing," 4.

31. Some argue that for more technologically advanced nations, the cumulative effect of past R&D investments might mean that they don't have to maintain the ratio that more rapidly growing developing nations seek.

32. Fleury, "Changes in Federal Academic Research Obligations by Field."

33. Fleury, "Changes in Federal Academic Research Obligations by Field."

34. National Science Foundation (NSF), "The State of U.S. Science and Engineering 2022."

35. NSF, "The State of U.S. Science and Engineering 2022."

36. NSF, "The State of U.S. Science and Engineering 2022."

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37. Strain, "Stapling Green Cards to Diplomas"; Neufeld, "STEM Immigration Is Critical to American National Security."

38. National Science Foundation (NSF), "Science and Engineering Indicators 2022."

39. NSF, "The State of U.S. Science and Engineering 2022."

40. National Science Foundation (NSF), "Women, Minorities, and Persons with Disabilities in Science and Engineering."

CHAPTER 2

1. I am indebted to retired Georgetown University professor Charles Weiss for contributions to this list.

2. See Holland, *Adaptation in Natural and Artificial Systems*; Holland, *Hidden Order*; Holland, *Emergence*; Holland, *Signals and Boundaries*; Holland, *Complexity*.

3. Kim and Mauborgne, "Value Innovation."

4. Schumpeter, *Capitalism, Socialism and Democracy*; Christensen, *The Innovator's Dilemma*.

5. Rich and Janos, *Skunk Works*.

6. Chposky and Leonsis, *Blue Magic*.

7. I am indebted to retired Georgetown University professor Charles Weiss for contributions to this list.

8. Nelson, *National Innovation Systems*, chapters 1 (with Nathan Rosenberg) and 16.

9. Freeman, *Technology, Policy and Economic Performance*, 1. For a recent review, see Atkinson, "Understanding the U.S. National Innovation System, 2020."

10. Nelson, *National Innovation Systems*, 3.

11. Quotations in this paragraph and the next two come from Nelson, *National Innovation Systems*, 4–6.

12. Price, *Geniuses at War*; McCartney, *Eniac*.

13. Nelson, *National Innovation Systems*, 8.

14. Edison's "invention factory" certainly pointed the way. John D. Rockefeller may have created the first modern industrial lab because of his understanding that Standard Oil's vertical monopoly relied on constant incremental technology advance in refining to stave off any potential competitors. See the discussion in Chernow, *Titan*.

15. Gertner, *The Idea Factory*.

16. An interesting aspect of the post–World War II Marshall Plan (as told in Weiss, "Eurasia Letter") built on how US firms at the end of the war understood the merger of mass production with mass marketing (in part because of the continental scale of US markets) far better than any other nation. One of the most successful elements of the Marshall Plan was a program implemented at very

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modest cost to educate 24,000 European business leaders (and later several thousand Japanese, Korean, and Taiwanese business leaders) at US business schools on how firms can to shift from a smaller-scale, often artisan-based, firm model into a US mass production/mass marketing model.

17. Prince Masayoshi Matsukata, a Meiji restoration leader and later minister of finance and prime minister, helped design the nineteenth- and early twentieth-century drive to finance Japan's rapid modernization through a strong export policy. See Reischauer, *Samurai and Silk*; and Sagers, *Origins of Japanese Wealth and Power*.

18. Johnson, *MITI and the Japanese Miracle*.

19. Schwab and Zahidi, "Global Competitiveness Report."

20. The discussion in this section is drawn from National Innovation Initiative, "Valuing Long-Term Innovation Strategies." See, for example, the discussion in Eustace, "The Intangible Economy," and key findings summarized in Intangible Economy, "Crafting Policy for the Information Age."

21. National Innovation Initiative, "Valuing Long-Term Innovation Strategies," 3.

22. Zambon et al., "A Literature Review on the Reporting of Intangibles," 6.

23. US Department of Transportation, "Annual U.S. Motor Vehicle Sales."

24. National Innovation Initiative, "Valuing Long-Term Investment Strategies," 11.

25. See, for example, Thum-Thysen et al., "Unlocking Investment in Intangible Assets."

26. This discussion draws on Gupta, *Done Deals*.

27. PitchBook Data and National Venture Capital Association (NCVA), "Venture Monitor 2021."

28. Gupta, *Done Deals*. Subsequent quotes in this section are also from Gupta.

29. Schultze, "Industrial Policy."

30. Sainsbury, *Windows of Opportunity*.

31. Krugman, *The Self-Organizing Economy*, 99.

32. Sainsbury, *Windows of Opportunity*. Sainsbury notes that the concept derives from the work of David Teece and others. See, for example, Pundziene and David, "New Applications of Dynamic Capability Research." For a review of the literature on this concept, see, for example, Menon and Mohanty, "Towards a Theory of 'Dynamic Capability' for Firms."

CHAPTER 3

1. Hart, *Forged Consensus*.

2. Hart, "Herbert Hoover's Last Laugh."

3. The material on Loomis here is drawn from Alvarez, "Alfred Lee Loomis," and Conant, *Tuxedo Park*.

4. Link, "Vannevar Bush."

5. The full list can be viewed at https://web.mit.edu/klund/www/books/radlab.html.

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6. Roosevelt, "Letter on the Office of Scientific Research and Development."

7. Bush, "Science, the Endless Frontier." The quotes that follow in this discussion come from this as well.

8. Turner, *The Frontier in American History*, ch. 1.

9. This discussion is largely drawn from Bonvillian, "Encompassing the Innovation Panoply."

10. Blanpied, "Inventing US Science Policy."

11. Singer, "Federally Supported Innovation."

12. Stokes, *Pasteur's Quadrant*.

13. Stokes, *Pasteur's Quadrant*, 89.

14. Shapley and Roy, *Lost at the Frontier*, 18.

CHAPTER 4

1. Congressman Vernon Ehlers (R-MI), a physicist who served on the US House Committee on Science and Technology, was among the first to use the term. See Ehlers, *Unlocking Our Future*, 40, 46; see also Branscomb and Auerswald, "Between Invention and Innovation," 4.

2. Branscomb and Auerswald, "Between Invention and Innovation."

3. Ruttan, "Induced Innovation and Agricultural Development."

4. Ruttan, *Is War Necessary for Economic Growth?*

5. Ruttan, *Is War Necessary for Economic Growth?*

6. Fong, "Breaking New Ground or Breaking the Rules," 152.

7. Fong, "Breaking New Ground or Breaking the Rules," 156.

8. Yannuzzi, "I-Q-Tel."

9. This account of the four periods is drawn from Bonvillian, "Emerging Industrial Policies in the United States," which in turn draws on a more detailed article, Bonvillian, "The New Model Innovation Agencies."

10. Bonvillian, Van Atta, and Windham, *The DARPA Model for Transformative Technologies*.

11. Stokes, *Pasteur's Quadrant*.

12. Fishman, *One Giant Leap*; Mindell, *Digital Apollo*.

13. Ruttan, *Is War Necessary for Economic Growth?*

14. Hughes, *Building the Next American Century*.

15. See 35 U.S.C. 200-212.

16. Bayh, Allen, and Bremer, "Universities, Inventors and the Bayh Dole Act"; Roessner, Bond, Okubo, and Planting, "The Economic Impact of Licensed Commercialized Inventions Originating in University Research."

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17. See PL 100-519, Title I, Sec. 102(d) (Oct. 24, 1988); 102 Stat. 2590; 15 USC Chapt. 7, Sec. 278k (Regional Centers for the Transfer of Manufacturing Technology); 15 CFR Sec. 290.6, http://www.mep.nist.gov/about-mep/legislative-history.htm.

18. National Institute of Standards and Technology (NIST), "30 Years of Advanced Manufacturing"; National Research Council, *21st Century Manufacturing*.

19. See 15 USC 638; US Small Business Administration, "About the SBIR and STTR Programs." A series of National Academies of Sciences studies of agency SBIR programs have supported their role. See the list of studies in National Research Council, *An Assessment of the SBIR Program*, viii, and "Findings and Recommendations."

20. Holtzman, "The Research and Development Tax Credit."

21. Browning and Shetler, *Sematech*; Hof, "Lessons from Sematech."

22. National Research Council, *The Advanced Technology Program*; Ruegg, Feller, and Bond, "A Toolkit for Evaluating Public R&D Investment."

23. Bonvillian, "Applying Innovation Policy to the U.S. Energy/Climate Challenge."

24. Bonvillian and Van Atta, "ARPA-E and DARPA."

25. See, for example, Good, "The Solyndra Scandal."

26. Bonvillian and Singer, *Advanced Manufacturing*, 15–64.

27. Nager, "Trade Vs. Productivity"; Nager and Atkinson, "The Myth of America's Manufacturing Renaissance."

28. See, for example, Atkinson, "U.S. Manufacturing Productivity Is Falling and It's a Cause for Alarm."

29. US Census Bureau, "International Trade in Goods and Services," Exhibit 5, "U.S. Trade in Goods (for 2020)."

30. US Census Bureau, "Trade in Goods with Advanced Technology Products," 2020 and 2019.

31. See, for example, Autor, Dorn, and Hanson, "The China Shock"; Spence, "The Impact of Globalization on Income and Employment."

32. President's Council of Advisors on Science and Technology, "Capturing Domestic Competitive Advantage in Advanced Manufacturing," 21–24; Bonvillian and Singer, *Advanced Manufacturing*, 131–86.

33. Gayle, Molnar, Roth, and Brunner, "Manufacturing USA 2019/2020 Highlights Report."

34. Gayle et al., "Manufacturing USA 2019/2020 Highlights Report," 6–7.

35. Bonvillian, "Restoring U.S. Leadership in Manufacturing"; Bonvillian, "Ensuring Manufacturing USA Reaches Its Potential."

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CHAPTER 5

1. Rosen, *Most Powerful Idea in the World*.

2. Quoted in Sennett, *The Craftsman*, 149. See also Rosen, *Most Powerful Idea in the World*, 36.

3. Bell, *The Hand*. See also Rosen, *The Most Powerful Idea in the World*, 36.

4. Dewey, *Education and Experience*.

5. Rosen, *The Most Powerful Idea in the World*, 37–38.

6. Bonvillian and Singer, *Advanced Manufacturing*, 15–18.

7. Quoted in Hart, "Reminiscences of James Watt."

8. Ericsson, Hoffman, Kozbelt, and Williams, *Cambridge Handbook of Expertise and Expert Performance*; Ericsson, Prietula, and Cokely, "The Making of an Expert." See also Rosen, *The Most Powerful Idea in the World*, 117–18.

9. Polanyi, *The Tacit Dimension*. See also Smith, "Michael Polanyi and Tacit Knowledge;" Rosen, *The Most Powerful Idea in the World*, 118.

10. Bonvillian and Singer, *Advanced Manufacturing*, 18.

11. Usher, *A History of Mechanical Inventions*; Rosen, *The Most Powerful Idea in the World,* 37–38.

12. Usher, *A History of Mechanical Inventions*, xv.

13. Usher, *A History of Mechanical Inventions*, 196–218.

14. Bennis and Biederman, *Organizing Genius*, 67.

15. See the discussion in Evans, *They Made America*, 152–71. See also Morris, *Edison*.

16. Evans, *They Made America*, 163–64.

17. Drawn from Bird and Sherwin, *American Prometheus*, 205–28, 255–59, 268–285, 293–97; Conant, *109 East Palace,* 106, 108, 110, 255.

18. Conant, *109 East Palace*, 255.

19. Drawn from Hoddeson and Daitch, *True Genius*, 127.

20. Hoddeson and Daitch, *True Genius*, 127–28.

21. Berlin, *The Man Behind the Microchip*, chaps. 3–8.

22. Williams, *Grace Hopper*, 68–98.

23. Williams, *Grace Hopper*, 69.

24. Williams, *Grace Hopper*, 68.

25. Gilbert, *Grace Murray Hopper*, 2–3.

26. Melfi, *Hidden Figures*.

27. Shetterly, *Hidden Figures*; Johnson, *Reaching for the Moon*.

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28. Johnson, *Reaching for the Moon*, 152–53.

29. Johnson, *Reaching for the Moon*, 197.

30. Drawn from Bennis and Biederman, *Organizing Genius*, 63–86.

31. Bennis and Biederman, *Organizing Genius*, 70.

32. Bennis and Biederman, *Organizing Genius*, 72.

33. Bennis and Biederman, *Organizing Genius*, 74.

34. Beahm, *I, Steve*, 30.

35. Bennis and Biederman, *Organizing Genius*, 77.

36. Bennis and Biederman, *Organizing Genius*.

37. Bennis and Biederman, *Organizing Genius*.

38. Bennis and Biederman, *Organizing Genius*, 77–78.

39. Drawn from Rich and Janos, *Skunk Works*, chap. 1.

40. Drawn from Hughes, *Genentech*; Evans, *They Made America*, 420–31.

41. Chrichton, *The Andromeda Strain*.

42. Wise, *The Andromeda Strain*.

43. Evans, *They Made America*, 425.

44. Trewin, "The Incredible Story of Genentech"; Hughes, *Genentech,* 99–100.

45. Evans, *They Made America*, 428.

46. Trewin, "The Incredible Story of Genentech," 2. See also Hughes, *Genetech,* 90–92, 132–34; Evans, *They Made America*, 428.

47. Morrow and Venter, *Oral History*, 3–53, 56–58; Venter, *A Life Decoded*, chap. 12; Shreeve, *The Genome War*.

48. Morrow and Venter, *Oral History*, 19.

49. Shreeve, *The Genome Wars*, 73; Morrow and Venter, *Oral History*, 18–19; Venter *A Life Decoded*, chap. 12.

50. For more, see Shreeve, *The Genome Wars*, 78.

51. Morrow and Venter, *Oral History*, 29.

52. Roberts, "Genome Patent Fight Erupts"; Morrow and Venter, *Oral History*, 31–33.

53. Venter et al., "Shotgun Sequencing of the Human Genome."

54. Venter et al., "The Sequence of the Human Genome."

55. Lander et al., "Initial Sequencing and Analysis of the Human Genome."

56. Wade, "Genetic Code of Human Life Is Cracked by Scientists."

57. Morrow and Venter, *Oral History*, 44–45.

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58. Morrow and Venter, *Oral History*, 56–57.

59. Drawn from Schein, DeLisi, Kampas, and Sonduck, *DEC Is Dead, Long Live DEC*.

CHAPTER 6

1. Bonvillian and Singer, *Advanced Manufacturing*, 24–31. Ideas in this chapter draw on chapters that I authored in Bonvillian et al., *The DARPA Model*.

2. Van Atta et al., *Transformation and Transition,* volumes 1 and 2; Van Atta, "Fifty Years of Innovation and Discovery."

3. Licklider, "Man-Computer Symbiosis."

4. Licklider, "Man-Computer Symbiosis"; Waldrop, *Dream Machine*, 175–87.

5. This discussion is drawn from Bonvillian and Singer, *Advanced Manufacturing*, 31–33.

6. Waldrop, *Dream Machine*, 198–203.

7. Waldrop, *Dream Machine*, 4–5.

8. Bennis and Biederman, *Organizing Genius*, 196–218.

9. Bonvillian, "The Connected Science Model for Innovation."

10. Waldrop, *Dream Machine*, 5. See also Engelbart, "The Mother of All Demos."

11. Bennis and Biederman, *Organizing Genius*, 63–86.

12. Hiltzik, *Dealers of Lightning*; Smith and Alexander, *Fumbling the Future*; Waldrop, *Dream Machine*, 331–94, 407–10.

13. Licklider, "Memorandum." See also Licklider and Clark, "Online Man-Computer Communication"; Waldrop, *Dream Machine*, 19.

14. Waldrop, *Dream Machine,* 19.

15. Licklider and Taylor, "The Computer as a Communication Device," 39; See also Waldrop, *Dream Machine,* 19.

16. Waldrop, *Dream Machine,* 375–80. See also Leiner et al., "A Brief History of the Internet."

17. Waldrop, *Dream Machine*, 462–465.

18. Waldrop, *Dream Machine*, 465.

19. Quoted in Fong, "ARPA Does Windows," 213.

20. Much of this section is drawn from Fong, "ARPA Does Windows."

21. Fong, "ARPA Does Windows," 215.

22. Hiltzik, *Dealers of Lightning*, xxv.

23. Fong, "ARPA Does Windows," 228; Licklider and Taylor, "The Computer as a Communication Device," 25.

24. This discussion is drawn from Bonvillian, "DARPA and Its ARPA-E and IARPA Clones."

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25. Solow, *Growth Theory, An Exposition*, 2nd ed.

26. Romer, "Endogenous Technological Change."

27. Nelson, *National Innovation Systems*. The innovation organization factor is discussed at length in Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 25–27, 181–86, 190–92.

28. Bush, "Science, The Endless Frontier."

29. Stokes, *Pasteur's Quadrant*.

30. Branscomb and Auerswald, "Between Invention and Innovation."

31. Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 181–86.

32. Bonvillian and Van Atta, "ARPA-E and DARPA."

33. Mazzucato, "Mission-Oriented Innovation Policies."

34. See Ruttan, *Is War Necessary for Economic Growth?* Although he did not use the term "extended pipeline," Ruttan wrote about the DOD's role in evolving these twentieth-century technologies.

35. Bonvillian, "The New Model Innovation Agencies."

36. Shapira and Youtie, "Next Production Revolution," 20.

37. Gertner, *The Idea Factory*.

38. See Bonvillian, "The Connected Science Model for Innovation."

39. Discussion drawn from Bonvillian, "Lessons from DARPA for Innovating in Defense Legacy Sectors," chap. 12 in Bonvillian et al., *The DARPA Model*.

40. Bonvillian, "Lessons from DARPA for Innovating in Defense Legacy Sectors."

41. Van Atta, "Fifty Years of Innovation and Discovery."

42. Bennis and Beiderman, *Organizing Genius*.

43. Bonvillian and Van Atta, "ARPA-E and DARPA," 483, 484.

44. Carleton, "The Value of Vision in Technological Innovation." See also Bonvillian and Van Atta, "ARPA-E and DARPA," 485.

45. See, for example, Cooper, Edgett, and Kleinschmidt, "Optimizing the Stage-Gate Process."

46. DARPA, "DARPA: Bridging the Gap Powered by Ideas," 1–10; DARPA, "DARPA over the Years." For a more detailed evaluation of these practices, see Bonvillian and Van Atta, "ARPA-E and DARPA."

47. Estes, "DARPA's Very Expensive, Sci-Fi Projects from the Future."

48. Roland, "Cloning DARPA." See also Roland and Shiman, *Strategic Computing*. For a different viewpoint on reasons for DARPA's success, see Fuchs, "Cloning DARPA Successfully."

49. Communication by Richard Van Atta to the author, November 13, 2017.

50. Bennis and Biederman, *Organizing Genius*, 206. See also Sen, "Transformative Innovation"; Sen, "Totally Radical."

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51. Sen, "Transformative Innovation."

52. Rich and Janos, *Skunk Works*.

53. Hiltzik, *Dealers of Lightning*.

54. Chposky and Leonsis, *Blue Magic*.

55. Bonvillian and Van Atta, "ARPA-E and DARPA," 486.

56. Bonvillian and Van Atta, "ARPA-E and DARPA," 476, 477, 492.

57. These technology challenges are detailed in Bonvillian, "All That DARPA Can Be."

58. Bonvillian, "DARPA and Its ARPA-E and IARPA Clones." Bonvillian and Van Atta, "ARPA-E and DARPA." For disclosure, please note that the present author was an advocate for ARPA-E and testified before the House Science Committee in support of ARPA-E legislation; worked for two months at DOE on its initial implementation; was involved in drafting HSARPA legislation while working in the US Senate; met with Japanese Parliament and government officials in Tokyo concerning Moonshot; met with German officials developing SPRIN-D in Berlin; and testified before the British Parliament on ARIA legislation.

59. Williams, *The First Seven Years*, vols. 1–3.

60. National Academies of Sciences, Engineering, and Medicine, *An Assessment of ARPA-E*, 125–132.

61. Bonvillian, "DARPA and its ARPA-E and IARPA Clones," 20.

62. Authorized by P.L 117-113, March 15, 2022. See National Institutes of Health (NIH), "Advanced Research Projects Agency for Health (ARPA-H)," https://www.nih.gov/arpa-h. The governmentwide omnibus appropriations bill for FY 2023 provided $1.5 billion in funding for ARPA-H, available through FY 2025. (https://democrats-appropriations.house.gov/sites/democrats.appropriations.house.gov/files/Labor%2C%20Health%20and%20Human%20Services%2C%20Education%2C%20and%20Related%20Agencies%20FY23%20Summary.pdf). See also Tollefson, "The Rise of 'ARPA-Everything" and What It Means for Science"; Collins, Schwetz, Tabak, and Lander, "ARPA-H"; Cook-Deegan, "Does NIH Need a DARPA?"

63. See https://www.aria.org.uk. See also *The Economist*, "A Growing Number of Governments Hope to Clone America's DARPA"; Mansfield and Owen, *Visions of ARPA*; ARIA, "Policy Statement."

64. These issues were discussed in Bonvillian, "The ARPA Model—U.S. Lessons for ARIA."

CHAPTER 7

1. This idea was embodied in Turner, *The Frontier in American History*, chap. 1.

2. Molloy, Smith, and Wozniak, *Declining Migration with the U.S.: The Role of the Labor Market*.

3. With the kind permission of Professor Charles Weiss, with whom these concepts were developed, this chapter is drawn from Bonvillian and Weiss, "Taking Covered Wagons East." See also Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*.

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4. Corporate Finance Institute, "Kondratieff Wave." These waves are named for the Russian economist Nikolai Kondratieff, who developed the theory in a 1925 book.

5. Freeman, "Innovation and Long Cycles of Economic Development"; Perez, *Technological Revolutions and Financial Capital*, 3–46; Atkinson, *The Past and Future of America's Economy*, 3–40.

6. See Spar, *Ruling the Waves*, where this concept of a well-defended status quo setting in after a freewheeling period without rules is developed.

7. Rycroft and Kash, "Innovation Policy for Complex Technologies."

8. Freeman, "Innovation and Long Cycles of Economic Development"; Freeman, Clark, and Soete, *Unemployment and Technical Innovation*.

9. Perez, *Technological Revolutions and Financial Capital*.

10. Abernathy and Utterback. "Patterns of Innovation in Technology"; Vernon, "International Investment and International Trade in the Product Cycle."

11. World Bank. "GDP Growth (Annual %): 1961–2021."

12. Adler, "Guiding Finance"; DiPippo et al., "Red Ink."

13. Material in this section is drawn from Bonvillian and Weiss, *Technological Innovation in Legacy Sectors,* 181–88.

14. Bush, *Science, the Endless Frontier*.

15. Stokes, *Pasteur's Quadrant*, 1–25, 45–89.

16. Buderi, *The Invention That Changed the World*.

17. See National Research Council, *Funding a Revolution,* 85–157, chaps. 4–5; Waldrop, *The Dream Machine*.

18. The business sector funds most of applied research (55 percent) and experimental development (86 percent). The federal government, universities, and nonprofits combined provide 69.4 percent of this basic research funding. See National Science Foundation (NSF), *Science and Engineering Indicators 2022*, fig. 18.

19. Bonvillian, "The New Model Innovation Agencies."

20. Singer, Federally Supported Innovation."

21. Branscomb and Auerswald, "Between Invention and Innovation."

22. Ruttan, *Technology Growth and Development*.

23. Ruttan, *Is War Necessary for Economic Growth?* Ruttan, the leading theorist behind the induced model, turned in this, his last book, to what we call here the "extended pipeline model," as well as the historic importance of the military in fostering radical and generative innovations (see chapter 4). See also Bonvillian, "The New Model Innovation Agencies," 425–33.

24. See, for example, Mazzucato, *The Entrepreneurial State*.

25. National Research Council, *Continuing Innovation in Information Technology*, fig. 1; Fong, "ARPA Does Windows."

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26. Mazzucato, *The Entrepreneurial State,* chap. 5. See, generally, Pisano and Shih, "Restoring American Competitiveness."

27. Ruttan, *Is War Necessary for Economic Growth?*; Bonvillian, "The Connected Science Model for Innovation," 206–7. See also Alic, Branscomb, Brooks, and Carter, *Beyond Spinoff*.

28. Roessner, Bond, Okubo, and Planting, "The Economic Impact of Licensed Commercialized Inventions Originating in University Research."

29. Fong, "Breaking New Ground or Breaking the Rules"; Bonvillian, "The New Model Innovation Agencies."

30. Discussion drawn from Bonvillian, "Advanced Manufacturing Policies and Paradigms for Innovation."

31. On Japan, see Womack, Jones, and Roos, *The Machine That Changed the World*; on Germany, see Berger, *Making in America*, 121–54.

32. US Bureau of Economic Analysis. "U.S. International Trade in Goods and Services (1960–2021)," table 1; Organisation for Economic Cooperation and Development (OECD), "Trade: Key Tables from OECD," table 3, January 8, 2013; Organisation for Economic Cooperation and Development (OECD), "Data: Current account balance, 1960–2022."

33. Morris, *The Dawn of Innovation*.

34. Berger, *Making in America*, 121–54; Nahm and Steinfeld, "Scale-up Nation"; Breznitz and Murphree, *Run of the Red Queen*.

35. Bonvillian, "The Connected Science Model for Innovation"; Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 13–36.

36. Branscomb and Auerswald, "Between Invention and Innovation"; Branscomb and Auerswald, *Taking Technical Risks*.

37. Wallace and Erickson, *Hard Drive*, 73, 139–206.

38. Womack et al., *The Machine That Changed the World*.

39. Programs at the Department of Agriculture, for example, can also be viewed as an extended pipeline model. These include support for agricultural research at land grant universities, the system of technology transfer through agriculture extension agents, and the network of price supports for different crops.

40. Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 124–33.

41. The steps described in this section are elaborated on in Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 44–124.

42. Branscomb and Auerswald, "Between Invention and Innovation."

43. This concept is discussed in Christensen, *The Innovator's Dilemma*.

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CHAPTER 8

1. Harden, "A Short History of the National Institutes of Health."

2. Price, "A Medical Anthropologist's Ruminations on NIH Funding."

3. Fauci, "Biodefence on the Research Agenda."

4. Buderi, *Where Futures Converge*, 106–8.

5. Buderi, *Where Futures Converge*, 160.

6. DiMasi, Grabowski, and Hansen, "Innovation in the Pharmaceutical Industry."

7. Vidyasagar, "Global Notes"; Commission on Health Research for Development, *Health Research*.

8. Centers for Medicare and Medicaid Services, "National Health Expenditure Accounts (NHEA)."

9. Kurani et al., "How Has U.S. Spending on Healthcare Changed over Time?"

10. Statista, "U.S. National Health Expenditure as Percent of GDP from 1960 to 2021."

11. Committee for a Responsible Federal Budget, "American Health Care." The report is based on Congressional Budget Office data on federal healthcare spending as a share of noninterest spending.

12. Extrapolations from U.S. Government Accountability Office, "The Nation's Fiscal Health."

13. National Research Council, *Enhancing the Vitality of the National Institutes of Health*.

14. National Research Council, *Enhancing the Vitality of the National Institutes of Health*, 4.

15. National Research Council, *Enhancing the Vitality of the National Institutes of Health*, 4–5.

16. National Research Council, *Enhancing the Vitality of the National Institutes of Health*, 5.

17. Varmus, *The Art and Politics of Science*, 174.

18. National Institutes of Health (NIH), "About the NIH Common Fund."

19. National Institutes of Health (NIH), "The Brain Initiative." Partners include DARPA, IARPA, NSF, and FDA.

20. National Institutes of Health (NIH), "NIH Establishes National Center for Advancing Translational Science."

21. See, for example, Promislo, "The NIH's Slow Response to the AIDS Epidemic and the Dismissal of Pasteur's Contributions."

22. Borrell, *The First Shots*, 42–51, 59–63.

23. Gross and Emanuel, "The Missing Part of a Pandemic Response."

24. See, generally, Dolgin, "The Tangled History of mRNA Vaccines;" Borrell, *The First Shots*, 100–4.

25. Dr. Michael V. Callahan, the former DARPA program manager and member of the clinical research faculty at Harvard Medical School and Massachusetts General Hospital, discussions with the author, January 28, 2022.

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26. Glim, "A Record-Breaking Sprint to Create a COVID-19 Vaccine"; Borrell, *The Frist Shots*, 42–51, 58–63, 93–95.

27. Wadman, "Long Covid Is a 'National Crisis.'"

28. Benen, "Departing NIH Chief Eyes More Research 'On Human Behavior.'"

29. Gross and Emanuel, "The Missing Part of a Pandemic Response."

30. Infectious Disease Society of America (IDSA), "IDSA Guidelines on the Treatment and Management of Patients with COVID-19."

31. Shreeve, *The Genome War*. See also Morrow and Venter, "Oral History"; Venter, *A Life Decoded*; Cook-Deegan, "Origins of the Human Genome Project"; Cook-Deegan, *The Gene Wars*.

32. US Department of Energy (DOE), "Human Genome Project Information Archive 1990–2003"; Cook-Deegan, "The Alta Summit, December 1984." The Alta Summit was a conference sponsored by the Department of Energy where knowledge advances were summarized that led to DOE's genomics efforts and later the Human Genome Project.

33. Golden and Lemonick, "The Race Is Over"; National Human Genome Institute. "20 Years Later, Genomicists Remember White House Event Announcing Draft Human Genome Sequence."

34. Zhang, "The Human Genome Is—Finally!—Complete."

35. Infectious Disease Society of America (IDSA), "Bad Bugs, No Drugs"; Boucher et al., "Bad Bugs, No Drugs: No ESKAPE!" One of the IDSA authors also wrote an updated article with more current data drawn on here; see Boucher, "Bad Bugs, No Drugs 2002–2020."

36. Centers for Disease Control and Prevention (CDC), "Antibiotic Resistance Threats in the United States 2019."

37. Centers for Disease Control and Prevention (CDC), "What is *C. diff*?"

38. Morgan et al., "Characteristics of Healthcare-Associated Infections Contributing to Unexpected In-Hospital Deaths."

39. US Food and Drug Administration (FDA), "Innovation/Stagnation"; US Food and Drug Administration (FDA), "FDA's Critical Path Initiative"; US Food and Drug Administration (FDA), "Critical Path Reports." This Critical Path effort was followed by a regulatory science initiative; see US Food and Drug Administration (FDA), "2021: Advancing Regulatory Science at FDA."

40. Biden, "Remarks"; Collins, Schwetz, Tabak, and Lander, "ARPA-H: Accelerating Biomedical Breakthroughs."

41. Sharp et al., "The Third Revolution."

42. Sharp and Langer, "Promoting Convergence in Biomedical Science." See also http://www.convergencerevolution.net/media.

43. National Science Foundation (NSF), "Learn About Convergence Research." The NSF views convergence research as one of its leading research challenges and has formed an Office of Integrative Activities and a Convergence Accelerator program in support of it. See National Science Foundation (NSF), "Growing Convergence Research at NSF; National Science Foundation (NSF),

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"Convergence Accelerator." Mihail Roco, an NSF scientist and leader on national nanotechnology policy efforts, was also a leader at NSF in forming convergence initiatives. See, for example, Roco, Bainbridge, Tonn, and Whitesides, *Convergence of Knowledge, Technology and Society*.

44. Hockfield, *The Age of Living Machines*, 15–16.

45. Buderi, *Where Futures Converge*, 272.

46. Sharp, Hockfield, and Jacks, *Convergence: The Future of Health*.

47. Sharp et al., *Convergence: The Future of Health*, 23–24.

48. National Institutes of Health (NIH), Brain Initiative, https://braininitiative.nih.gov.

49. National Institutes of Health (NIH), *All of Us* Research Program, https://allofus.nih.gov; Kaiser, "NIH Open Precision Medicine Study to Nation."

50. "Patent Rights in Inventions Made with Federal Assistance" (Bayh-Dole Act), 35 US Code Chapter 18, Sections 200–212.

51. Bourla, *Moonshot*, 116–26.

52. HR 5376, Inflation Reduction Act of 2022, 117th Congress, 2nd Sess., 2022, Subtitle B, Part 1, https://www.congress.gov/bill/117th-congress/house-bill/5376. Under the provisions, beginning in 2026, the Centers for Medicare and Medicaid Services must negotiate, in stages, maximum prices for 100 brand-name drugs that account for the greatest Medicare spending and do not have generic equivalents. Noncomplying companies face civil penalties and excise taxes.

53. Adler, "Inside Operation Warp Speed."

54. Drawn from Bonvillian, "Emerging Industrial Policy Policies in the United States." See also Bonvillian, "Operation Warp Speed."

55. Cohen, "The United States Badly Bungled Coronavirus Testing."

56. Institute of Medicine, "Financing Vaccines in the 21st Century," 107–8.

57. Schneider et al, "Impact of U.S. COVID-19 Vaccination Efforts." Studies have estimated that vaccines saved nearly 20 million lives worldwide in 2021. See Watson et al., "Global Impact of the First Year of COVID-19 Vaccination."

58. The role of change agents in innovation is discussed in Bonvillian and Weiss, *Technological Innovation in Legacy Sectors,* 186–88, 213–14.

59. Adler, "Inside Operation Warp Speed."

60. Bancel, "The First COVID-19 Vaccine in the Clinic"; Vardi, "The Race Is On"; Gelles, "The Husband-and-Wife Team Behind the Leading Vaccine to Solve Covid-19."

61. Dolgin, "The Tangled History of mRNA Vaccines." The brief history is as follows: Two researchers, Katalin Karikó and Drew Weissman at the University of Pennsylvania, had discovered ways to increase mRNA's therapeutic potential in 2005, altering part of the mRNA code to enable it to move past cell immune defenses, persisting in their research despite lack of NIH support. Dan Wattendorf, as a DARPA program manager, launched a DARPA project to rapidly develop vaccines focused on mRNA, funding new biotech companies, including $25 million to

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Moderna, to advance vaccine development. Moderna had completed phase 1 clinical trials for an mRNA vaccine by 2019 for the Zika virus. Work in nanolipids for delivery by Robert Malone and others, and by Barney Graham, Jason McLellan, and Kizzmekia Corbet and colleagues through NIH on the structure of the COVID-19 spike protein, also led to advances. See Johnson, "A One-Way Ticket"; Johnson, "A Scientific Hunch"; Sonne, "How a Secretive Pentagon Agency Seeded the Ground for a Rapid Coronavirus Cure"; Dolgin, "How COVID Unlocked the Power of RNA Vaccines"; Johnson, "Serendipity and Foresight Prepared the World to Fight the Coronavirus"; Geddes, "Taming the Spike"; Branswell, "Kizzmekia Corbett"; Borrell, *The First Shots*, 42–51, 58–63. For a summary of DARPA's numerous COVID-19 efforts, see https://www.darpa.mil/work-with-us/covid-19.

62. Slaoui and Hepburn, "Developing Safe and Effective Covid Vaccines."

63. Bancel, "Moderna's Path to Vaccine Innovation"; Mitropoulos, "The 35-Year-Old Scientist Who Led Moderna's Efforts to Create a COVID-19 Vaccine."

64. Bourla, *Moonshot*; Vardi, "The Race Is On"; Miller, *The Vaccine*.

65. OWS focused on vaccines, not personal protective equipment; Donald Trump's administration left that problem for states to solve, with some exceptions. One state's efforts to tackle it is reviewed in Reynolds, Traficonte, and Waldman-Brown, "Strengthening Manufacturing Innovation Ecosystems Before, During, and After Covid."

66. Slaoui and Hepburn, "Developing Safe and Effective Covid Vaccines."

67. Adler, "Inside Operation Warp Speed."

68. Exacerbating the problem, CDC set vaccination priorities in an impractical way, allowing all health workers, and then the most elderly, to go first since they were most at risk of dying, but then creating a second priority that bundled together most of the rest of the population, combining social equity concerns with risk. This created a disorderly administration process in most states, with countless individuals jockeying with each other on state and local online sites trying to get vaccination appointments.

CHAPTER 9

1. Solow, *Growth Theory*, ix–xxvi.

2. Romer, "Endogenous Technological Change."

3. This chapter is drawn from Bonvillian and Singer, "What Economists Don't Know About Manufacturing," and Bonvillian and Singer, *Advanced Manufacturing*.

4. See, generally, Adler and Bonvillan, "America's Advanced Manufacturing Problem—and How to Fix It."

5. Bonvillian and Singer, *Advanced Manufacturing,* 178–83.

6. Bonvillian and Singer, *Advanced Manufacturing*, 53 (and notes therein).

7. MDM Staff, "MAPI Foundation: Full Recovery in Sight."

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8. Armstrong, Bonvillian, and Berger, "Advanced Technology, Advanced Training," 7, fig. 1; OECD Productivity Database, https://stats.oecd.org/Index.aspx?DataSetCode=PDBI_I4.

9. Bureau of Labor Statistics, "Monthly Labor Review," https://www.bls.gov/opub/mlr/2018/article/multifactor-productivity-slowdown-in-us-manufacturing.htm; Converged, "American Manufacturing Statistics," https://www.propelplm.com/blog/american-manufacturing-statistics. From 2007 to 2020, US manufacturing saw nearly no gain in productivity; it was a mere 0.4 percent more productive during that period.

10. National Research Council, *21st Century Manufacturing*, 32, fig. 2.2.

11. Stewart and Atkinson, "Restoring America's Lagging Investment in Capital Goods," 1; Atkinson, Stewart, Andes, and Ezell, "Worse Than the Great Depression," 47–58. For recent data, see US Bureau of Economic Analysis, Investments in Private Fixed Assets by Industry, Current-Cost Net Stock of Private Fixed Assets by Industry, 2000–2021, https://apps.bea.gov/iTable/?ReqID=10&step=2#eyJhcHBpZCI6MTAsInN0ZXBzIjpbMiwzXSwiZGF0YSI6W1siVGFibGVfTGlzdCIsIjIxIl1dfQ==.

12. Armstrong, Bonvillian, and Berger, "Advanced Technology, Advanced Training," 19, fig. 7.

13. White House, "Early Signs That Bidenonomics Is Attracting New Foreign Investment in U.S. Manufacturing." Council of Economic Advisors, August 23, 2023. https://www.whitehouse.gov/cea/written-materials/2023/08/23/early-signs-that-bidenomics-is-attracting-new-foreign-investment-in-u-s-manufacturing/.

14. Bureau of Labor Statistics, "Quarterly Census of Employment and Wages, Series ID ENUUS00020531-33, Table: Number of US Private Manufacturing Establishments in NAICS Code 31-33, all sizes, 2000–2013. http://data.bls.gov/pdq/SurveyOutputServlet.

15. Armstrong et al., "Advanced Technology, Advanced Workforce," 18, fig. 6.

16. Berger, "How the Financial Sector Gutted Manufacturing."

17. Wessner, "Entrepreneurship and the Innovation Ecosystem Policy." Wessner first identified the concept of the industrial ecosystem. The history of the term is explored in Granstrand and Holgersson, "Innovation Ecosystems." Sujay Shivakumar has pointed out that while ecosystems are thought of as biological, there are social ecosystems that face a deep problem of collaboration to be successful. These social ecosystems have many points of entry, adding to their complexity; they are made up of networks within a network, and a "trust network" is needed in economic ecosystems, which would include industrial ecosystems. Shivakumar, Center for Strategic and International Studies, discussions with the author, June 28, 2022.

18. Berger, *Making in America*.

19. Small Business Administration, "Frequently Asked Questions About Small Business, Small Businesses Comprise What Share of the U.S. Economy" (SBA Sept. 2012). https://www.sba.gov/sites/default/files/FAQ_Sept_2012.pdf.

20. Mahoney and Helper, "Ensuring American Manufacturing Leadership Through Next-Generation Supply Chains."

21. Armstrong et al., "Advanced Technology, Advanced Workforce," 23, fig. 8.

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22. Bonvillian and Singer, *Advanced Manufacturing,* 185–215.

23. National Science Foundation (NSF), "The State of U.S. Science and Engineering: U.S. and Global Research and Development," https://ncses.nsf.gov/pubs/nsb20221/u-s-and-global-research-and-development, fig. 17.

24. Autor et al., "Foreign Competition and Domestic Innovation," 2; Helper, Krueger, and Wial, "Why Does Manufacturing Matter? Which Manufacturing Matters?"

25. Armstrong et al., "Advanced Technology, Advanced Workforce," 13, fig. 3.

26. Bonvillian and Sarma, *Workforce Education*, 36–38, 77–80.

27. Sarma and Bonvillian, "The Quest for Quality Jobs"; Sarma and Bonvillian, "Fixing an Imperfect Labor Market Information System."

28. Bonvillian and Sarma, *Workforce Education*.

29. Atkinson, *The Past and Future of America's Economy*, 3–40. See, generally, Perez, *Technological Revolutions and Financial Capital*, 3–46. The quality manufacturing wave, discussed next, was led in the 1970s and 1980s by Japan.

30. Ruttan, *Is War Necessary for Economic Growth?*

31. Berger, *How We Compete*, 251–77.

32. Nicholson, "What Is Made in America?"

33. Nicholson, "What Is Made in America?"

34. Helper and Krueger, "Supply Chains and Equitable Growth," 12–14.

35. Economic Policy Institute, "U.S. Trade Deficits Hit Record Highs in 2021," https://www.epi.org/blog/u-s-trade-deficits-hit-record-highs-in-2021-more-effective-trade-industrial-and-currency-policies-are-needed-to-create-more-domestic-manufacturing-jobs/ (citing US Census Bureau data); Statista, "Trade Deficit of Goods Manufactured in the United States from 2000 to 2016," https://www.statista.com/statistics/814589/manufactured-goods-trade-deficit-us/.

36. US Census Bureau, "Trade in Goods with Advanced Technology Products," https://www.census.gov/foreign-trade/balance/c0007.html.

37. World Bank, "Manufacturing, Value Added (current US$)—China, United States," https://data.worldbank.org/indicator/NV.IND.MANF.CD?locations=CN-US.

38. Statista, "China Is the World's Manufacturing Superpower," https://www.statista.com/chart/20858/top-10-countries-by-share-of-global-manufacturing-output/.

39. US Trade Representative, "The People's Republic of China," https://ustr.gov/countries-regions/china-mongolia-taiwan/peoples-republic-china.

40. Nahm and Steinfeld, "Scale-up Nation," 289–90; see also Breznitz and Murphree, *Run of the Red Queen*.

41. Nahm and Steinfeld, "Scale-up Nation," 294.

42. Nahm and Steinfeld, "Scale-up Nation," 295–98.

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43. DiPippo et al., "Red Ink."

44. Adler, "Guiding Finance."

45. Bonvillian, "Donald Trump's Voters and the Decline of American Manufacturing."

46. Some 35 percent of adults in the US describe themselves as "working class." Jones, "Middle-Class Identification Steady in the U.S." See also Thompson, Hickey, and Thompson, *Society in Focus*, 200–5.

47. Kearney, Hershbein, and Jácome, "Profiles of Change."

48. Kearney et al., "Profiles of Change."

49. Federal Reserve Bank of New York, "The Labor Market for Recent College Graduates, Wages, Distribution of Annual Wages for Recent College Graduates (compared to High School Diploma), 2021." https://www.newyorkfed.org/research/college-labor-market#--:explore:wages.

50. Mislinski, "Household Incomes."

51. Freeman, *America Works*.

52. Goldin and Katz, *The Race Between Education and Technology*.

53. David Autor, Arindrajit Dube, and Annie McGrew. "Unexpected Compression: Competition at Work in the Low Wage Labor Market." NBER Working Paper 31010. National Bureau of Economic Research, Cambridge, MA, November 2023. https://shapingwork.mit.edu/wp-content/uploads/2023/11/Autor_Dube_McGrew_Nov-2023.pdf.

54. Stettner, Yudken, and McCormack, "Why Manufacturing Jobs Are Worth Saving."

55. See Autor, Dorn, and Hanson, "The China Shock."

56. Scott and Mokhiber, "Growing China Trade Deficit Cost 3.7 Million American Jobs." Another study found 2.4 million US jobs lost between 1999 and 2011; see Autor et al., "The China Shock."

57. Spence, "The Impact of Globalization on Income and Employment."

58. St. Louis Federal Reserve Bank, "All Employees, Manufacturing," https://fred.stlouisfed.org/series/MANEMP. See also Scott, "Manufacturing Job Loss." See detailed review of manufacturing job loss in Atkinson et al., "Worse Than the Great Depression."

59. Bureau of Labor Statistics, "Industries at a Glance," https://www.bls.gov/iag/tgs/iag31-33.htm.

60. Bonvillian and Singer, *Advanced Manufacturing*, 60–61.

61. Meckstroth, "The Manufacturing Value Chain Is Bigger Than You Think."

62. Bonvillian, "Donald Trump's Voters and the Decline of American Manufacturing," 31.

63. Berger, *Making in America*, 28–33.

64. Nager, "Trade Vs. Productivity"; Scott, "Manufacturing Job Loss."

65. US Census Bureau, "Trade in Goods with Advanced Technology Products, 2022," https://www.census.gov/foreign-trade/balance/c0007.html.

66. Mishel, "Yes, Manufacturing Still Provides a Pay Advantage."

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67. Audretsch, "Why Is Germany So Strong in Manufacturing?" 1–2.

68. Christensen, *The Innovator's Dilemma*.

69. Nahm and Steinfeld, "Scale-up Nation," 297–98.

70. US Census Bureau, "Trade in Goods with Advanced Technology Products."

71. Nager, "Trade Vs. Productivity"; Scott, "Manufacturing Job Loss."

72. Goldstein, *Janesville*.

73. Samuelson, "Where Ricardo and Mill Rebut and Confirm Arguments of Mainstream Economists Supporting Globalization," 135–37, 144–45. This work builds on the author's earlier Stolper-Samuelson theorem, which states that where there are two goods and two factors of production (capital and labor), and specialization remains incomplete, one of the two factors—the one that is scarcer—must end up worse off in absolute terms as a result of opening up to international trade. This idea, that there are winners and losers from the liberalization of international trade, anticipated the effect of globalization on developed nation wages and income distribution. See Stolper and Samuelson, "Protection and Real Wages."

74. Samuelson, "Where Ricardo and Mill Rebut and Confirm Arguments of Mainstream Economists Supporting Globalization," 137.

75. See, for example, Stec, "The Implications of American Wage Stagnation"; Reeves, Pullam, and Ashley, "Are Wages Rising, Falling, or Stagnating?" While wages grew in 2021, that gain was offset by inflationary prices. See Furman and Powell, "US Wages Grew at Fastest Pace in Decades in 2021, But Prices Grew Even More."

76. Autor et al., "Unexpected Compression."

77. Samuelson, "Where Ricardo and Mill Rebut and Confirm Arguments of Mainstream Economists Supporting Globalization," 137.

78. Rodrik, *Straight Talk on Trade*.

79. Rodrik, *Straight Talk on Trade*, ix, x. See also Berger, "Globalization Survived Populism Once Before."

80. Samuelson, "Where Ricardo and Mill Rebut and Confirm Arguments of Mainstream Economists Supporting Globalization," 143.

81. Schultze, "Industrial Policy: A Dissent."

82. Nelson, "Building Effective Innovation Systems," 7.

83. Compare Atkinson, "Potato Chips, Computer Chips"(computer chips have higher productivity, job creation, and national security aspects) with Bhagwati, "The Computer Chip vs. Potato Chip Debate" (it is an error to favor computer chips over potato chips as a more valuable sector).

84. These issues, including the advanced manufacturing institutes, are discussed in detail in Bonvillian and Singer, *Advanced Manufacturing*, 101–86.

85. Bonvillian and Singer, *Advanced Manufacturing*, 34.

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86. Bonvillian and Singer, *Advanced Manufacturing*, 101–86.

87. Uchitelle, *Making It*, citing Bureau of Economic Analysis data.

88. Hockfield, Liveris, Advanced Manufacturing Partnership Working Group, and Advanced Manufacturing Partnership Steering Committee, "Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing"; Advanced Manufacturing Partnership, "Report to the President: Accelerating U.S. Advanced Manufacturing."

89. Berger, *Making in America*, 20.

90. National Academies of Sciences, Engineering, and Medicine, *Long-Term Participation by DOD in Its Manufacturing Innovation Institutes*, table 3.3. Germany's Fraunhofer Institute program invests approximately $2.8 billion annually from public and private sources in manufacturing technology advances and related programs (https://www.fraunhofer.de/en/about-fraunhofer/profile-structure/facts-and-figures/finances.html). China has invested in a range of manufacturing efforts that have greatly outpaced the level of US efforts; see Congressional Research Service, "'Made in China 2025' Industrial Policies." In contrast, US federal investments in advanced manufacturing institutes are about $200 million/year.

91. Advanced Manufacturing Partnership, "Report to the President on Ensuring American Leadership in Advanced Manufacturing"; Advanced Manufacturing Partnership, "Report to the President: Accelerating U.S. Advanced Manufacturing"; Pisano and Shih. *Producing Prosperity*; Berger, *Making in America*; Uchitelle, *Making It;* Bonvillian and Singer, *Advanced Manufacturing*.

92. See recommendations in Bonvillian, "Ensuring Manufacturing USA Reaches Its Potential."

93. National Association of Manufacturers, "2019 United States Manufacturing Facts," https://www.nam.org/state-manufacturing-data/2019-united-states-manufacturing-facts/.

94. National Institute of Standards and Technology (NIST), "Manufacturing USA Highlights Report."

95. See, for example, Vittoria Elliott, "Twitter Really Is Worse than Ever," Wired, May 3, 2023, https://www.wired.com/story/twitter-really-is-worse-than-ever/#:~:text=Under%20Elon%20Musk%2C%20hate%20speech,and%20propaganda%20accounts%20have%20thrived.&text=A%20year%20ago%2C%20Elon%20Musk,place%20for%20unfettered%20free%20speech.

96. Walter Isaacson, *Elon Musk* (New York: Simon and Shuster, 2023).

97. Keynes, *The General Theory of Employment, Interest and Money*.

98. Friedman, *The Moral Consequences of Economic Growth*.

CHAPTER 10

1. See, generally, Adams, *Home Fires*.

2. Pain, "Power Through the Ages."

3. US Energy Information Administration, "U.S. Energy Facts Explained," https://www.eia.gov/energyexplained/us-energy-facts/.

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4. United Nations Framework Convention of Climate Change, "The Paris Agreement," https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

5. Pacala and Socolow, "Stabilization Wedges."

6. Pacala and Socolow, "Stabilization Wedges."

7. See, for example, Podesta, Stern, and Batten, "Capturing the Energy Opportunity." These authors argue that the technology needed for an energy low-carbon transformation exists and that the investment dollars are available, assuming that adequate policies are implemented.

8. Statista, "Number of Motor Vehicles Registered in the United States from 1990 to 2021," https://www.statista.com/statistics/183505/number-of-vehicles-in-the-united-states-since-1990/; Argonne National Laboratory, https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates.

9. US Department of Transportation, Bureau of Transportation Statistics, "Average Age of Automobiles and Trucks in the United States," https://www.bts.gov/content/average-age-automobiles-and-trucks-operation-united-states (this includes passenger cars and light trucks).

10. The ideas in this section draw on Weiss and Bonvillian, *Structuring an Energy Technology Revolution*.

11. Cunliffe, "Energy Innovation in the FY 2021 Budget," figs. 2–3.

12. Nemet and Kammen. "U.S. Energy Research and Development."

13. International Energy Agency, *Clean Energy Innovation*.

14. Nemet and Kammen. "U.S. Energy Research and Development."

15. Neal, Smith, and McCormick, *Beyond Sputnik*, fig. 5.3 "U.S. Energy R&D Spending vs. Price of Crude Oil."

16. International Energy Agency, Net Zero by 2050—A Roadmap for the Global Energy Sector, 2021, page 29, https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

17. International Energy Agency, *Energy Technology Perspectives 2008*, 39.

18. International Renewable Energy Agency, *World Energy Transitions Outlook 2022*. Investment needs total $5.7 trillion per year until 2030, including a requirement to redirect $700 billion annually away from fossil fuels to avoid stranding assets.

19. Bloomberg New Energy Financing, "Energy Transition Investment Trends 2022."

20. International Energy Agency, Net Zero by 2050—A Roadmap for the Global Energy Sector, 2021, page 29, https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

21. Bonvillian and Weiss, Technological Innovation in Legacy Sectors, 15, 55–66.

22. This discussion is drawn from Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 44–124.

23. This section is drawn from Bonvillian, "Applying Innovation Policy to the U.S. Energy/Climate Challenge."

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24. Discussed in Atkinson and Hackler, "Economic Doctrines and Approaches to Climate Change Policy."

25. See, for example, Fox, "From 'Economic Man' to Behavioral Economics."

26. The Clean Air Act Amendments of 1990, 104 Stat. 2468, P.L. 101–549. https://www.govinfo.gov/content/pkg/STATUTE-104/pdf/STATUTE-104-Pg2399.pdf.

27. United Nations Environment Programme, "Treaties," https://ozone.unep.org/treaties/montreal-protocol.

28. The American Clean Energy and Security Act of 2009, 111th Cong., 1st Sess., H.R. 2454 (Waxman-Markey Bill) passed the House of Representatives on June 26, 2009; the vote was 219–212. The Senate version of the legislation did not pass. See the American Power Act of 2010 (the Kerry-Lieberman bill), which became S. 1733, 111th Cong., 2nd Sess. (released May 12, 2010). This legislation descended from three earlier versions of the Climate Stewardship Act introduced in 2003 (S. 139), 2005 (S. 1151), and 2007 (S. 280) by Senators Joseph Lieberman and John McCain. In the interest of disclosure, this author worked on developing this cap-and-trade legislation.

29. DOE Energy Frontier Research Centers, https://science.osti.gov/bes/efrc.

30. DOE Hubs, https://www.energy.gov/science-innovation/innovation/hubs.

31. Bonvillian and Van Atta, "ARPA-E and DARPA."

32. DOE SunShot Initiative, https://www.energy.gov/eere/solar/sunshot-initiative.

33. DOE Clean Energy Manufacturing Initiative, https://www.energy.gov/eere/cemi/about-clean-energy-manufacturing-initiative; Advanced Manufacturing Office, https://www.energy.gov/eere/amo/advanced-manufacturing-office.

34. US Department of Energy (DOE), "Office of Technology Transitions," https://www.energy.gov/technologytransitions/office-technology-transitions.

35. Clark, "Renewable Energy R&D Funding History"; see also MIT Energy Initiative, "The Future of Solar Energy."

36. US Department of Energy (DOE), Loan Programs Office, https://www.energy.gov/lpo/loan-programs-office.

37. On DOD's role, see generally Alic, Sarewitz, Weiss, and Bonvillian, "A New Strategy for Energy Innovation"; and Bonvillian, "DOD's Role in Energy Innovation."

38. Center for Climate and Energy Solutions, "Regulating Power Sector Carbon Emissions," https://www.c2es.org/content/regulating-power-sector-carbon-emissions/. However, a 2022 Supreme Court case overturned the authority of the US Environmental Protection Agency (EPA) to place caps on utility carbon emissions. See *West Virginia vs. Environmental Protection Agency*, No. 20-1530, 597 U.S., decided June 30, 2022, https://www.supremecourt.gov/opinions/21pdf/20-1530_n758.pdf.

39. US Environmental Protection Agency (EPA), "Transportation, Air Pollution, and Climate Change," https://www.epa.gov/transportation-air-pollution-and-climate-change.

40. US Department of Energy (DOE), "Appliance and Equipment Standards Program," https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program.

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41. California Public Utilities Commission, https://www.cpuc.ca.gov/-/media/cpuc-website/files/legacyfiles/e/5304-eesp-onepager.pdf.

42. US Department of Energy (DOE), "Renewable Energy Explained," https://www.eia.gov/energyexplained/renewable-sources/portfolio-standards.php.

43. This section is drawn from Bonvillian and Van Atta, "ARPA-E and DARPA." In the interest of disclosure, this author was involved in advocating for and standing up ARPA-E.

44. Defense Advanced Research Projects Agency (DARPA), https://www.darpa.mil/news-events/2022-08-31.

45. ARPA-E Overview, https://arpa-e.energy.gov/sites/default/files/ARPA-E%20Fact%20Sheet_051522.pdf.

46. See, generally, National Academies of Sciences, Engineering, and Medicine, *An Assessment of ARPA-E*.

47. International Energy Agency, "Net Zero by 2050."

48. Gaddy, Sivaram and O'Sullivan, "Venture Capital and Cleantech," 2–3.

49. Gaddy et al., "Venture Capital and Cleantech," 5, 9.

50. Weyant, Fu, and Bowerstock, *Renewed Energy*.

51. Temple, "How VCs Can Avoid Another Bloodbath."

52. Statista, https://www.statista.com/statistics/499193/clean-energy-investment-in-the-us/; Bloomberg New Energy Financing, "Energy Transition Investment Trends 2022"; St. John, "The Rules for Early-Stage Cleantech Venture Capital Investment in 2021."

53. Bergen, "The Investors Putting Billions Into Climate Tech Don't Plan to Stop Now."

54. National Venture Capital Association, "Six Charts That Show 2021's Record Year for US Venture Capital," https://pitchbook.com/news/articles/2021-record-year-us-venture-capital-six-charts; US Energy System Facts, "U.S. Energy System Factsheet," https://css.umich.edu/publications/factsheets/energy/us-energy-system-factsheet.

55. Reif, "A Better Way to Deliver Innovation to the World." This and the following three examples are discussed in greater detail in Singer and Bonvillian, "Innovation Orchards."

56. The Engine, Built by MIT, "About Us," https://www.engine.xyz/about-us/our-mission/.

57. MIT News Office, "The Engine Announces Second Round of Funding to Support 'Tough Tech' Companies."

58. MIT News Office, The Engine Expands"; The Engine, "The Engine Expansion."

59. Cyclotron Road, "About Us," https://cyclotronroad.lbl.gov/about-us.

60. Cyclotron Road, "Activating Tomorrow's Technology Leaders."

61. Activate, "The World Needs Scientists More Than Ever," https://www.activate.org/mission.

62. Nazemi, "From Startup to Scale-up"; communications by the author with Peter Russo, MassMEP, and Micaelah Morrill, Greentown Labs, February 2016.

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63. This discussion draws on Hart, Bonvillian, and Austin, "Energy Storage for the Grid."

64. The idea was introduced in Utterback and Abernathy, "A Dynamic Model of Process and Product Innovation."

65. MIT Energy Initiative, "The Future of Energy Storage, xi.

66. International Energy Agency, "Tracking Clean Energy Progress 2017," 623, fig. 59.

67. Hart, Bonvillian, and Austin, "Energy Storage for the Grid," 23–24.

68. MIT Energy Initiative, "The Future of Energy Storage," xv.

69. MIT Energy Initiative, "The Future of Energy Storage," xv.

70. Hart, Bonvillian, and Austin, "Energy Storage for the Grid," 24–25.

71. Hart et al., "Energy Storage for the Grid," 17–18.

72. Hart et al., "Energy Storage for the Grid," 25.

73. Bonvillian and Singer, *Advanced Manufacturing*, 57–58.

CHAPTER 11

1. Lewis, "Innovation, Technical Skills, and Vocational Education and Training."

2. For a more detailed review of three of these sectors, see Bonvillian and Sarma, *Workforce Education*, 75–97.

3. See Bonvillian, "Advanced Manufacturing and the Construction Sector."

4. Bonvillian and Sarma, *Workforce Education*, 41, 221–23.

5. Kennedy, Fry, and Funk, "6 Facts about America's STEM Workforce and Those Training for It." The potential gains from being in the STEM workforce are not equally shared, as the NSF "State of U.S. Science and Engineering 2022" figures show. Women hold 48 percent of US jobs overall, but they comprise only 34 percent of the STEM workforce. Minorities comprise some 30 percent of the employed workforce but hold only 23 percent of total STEM jobs.

6. Rockwell, "The Hidden STEM Economy."

7. National Science Foundation (NSF), "The State of U.S. Science and Engineering 2022." US students rank seventh out of thirty-seven OECD countries in science literacy, but only twenty-fifth in mathematics literacy. The average US science score has been improving, but the math average has not changed significantly since 2003. Black, Latino, and Native American students in underachieving high-minority or high-poverty population schools persistently score low on science literacy measures; these schools have science and math faculty with the least experience teaching in their fields—and more experience helps improve scores.

8. National Center for Education, National Assessment of Education Progress (NAEP), "NAEP Report Card." NAEP, a standardized test administered to K–12 students across the US every two years, found in 2019 that only 41 percent of fourth- and eighth-grade students and 21 percent of twelfth-grade students were "proficient" in mathematics.

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9. National Science Foundation (NSF), "The State of U.S. Science and Engineering 2022." Data from 2019 appear to be a more reliable benchmark because international travel was so disrupted by the COVID-19 pandemic; international student numbers appeared to be recovering to close to 2019 levels by late 2021.

10. NSF, "The State of U.S. Science and Engineering 2022." Typically, three-fourths of these doctorate recipients state an intention live in the US in the year after graduation, but data on numbers actually staying is difficult to compile.

11. NSF, "The State of U.S. Science and Engineering 2022."

12. Athanasia and Cota, "The U.S. Should Strengthen STEM Education to Remain Globally Competitive."

13. According to Athanasia and Cota, some 28 percent of US public school teachers hired to teach science in grades 7–12 do not hold a degree (or even a minor) in the sciences or science education. Athanasia and Cota, "The U.S. Should Strengthen STEM Education to Remain Globally Competitive." They reference a 2008 study found that that 40 percent of mathematics classes in high-poverty schools across the US were taught by teachers without a degree in the subject; see Education Trust, "Core Problems."

14. US Department of Defense (DOD), "Fiscal Year 2020 Industrial Capabilities Report to Congress," 112.

15. National Academies of Sciences, Engineering and Medicine, *Call to Action for Science Education*, 8.

16. Romer, "Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?"

17. Romer, "Should the Government Subsidize Supply or Demand," 4.

18. Romer, "Should the Government Subsidize Supply or Demand," 35.

19. Goldin and Katz, "The Future of Inequality"; Goldin and Katz, *The Race Between Education and Technology*.

20. US Census Bureau, "Census Bureau Releases New Educational Attainment Data."

21. Torpey, "Got Skills?"

22. "See, generally, Brundate, "Profile of the Labor Force by Educational Attainment."

23. Carnevale, Jayasundera, and Gulish, "America's Divided Recovery."

24. Becker, *Human Capital*.

25. Bonvillian and Sarma, *Workforce Education*, 44–46.

26. Council of Economic Advisors, "Active Labor Market Policies"; See also Council of Economic Advisors, "Economic Report of the President"; Council of Economic Advisors, "Addressing America's Reskilling Challenge."

27. US Department of Labor, "Registered Apprenticeship National Results Fiscal Year 2021," https://www.dol.gov/agencies/eta/apprenticeship/about/statistics/2021.

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28. Holzer, "Workforce Development as an Antipoverty Strategy," 1.

29. Community College Research Center, "Community College FAQs," https://ccrc.tc.columbia.edu/community-college-faqs.html.

30. Gold, "Two-Thirds of Adults Have Less Than a Four-Year Degree."

31. Bonvillian and Sarma, *Workforce Education*, 165–66, 222–23.

32. Bonvillian and Sarma, *Workforce Education*, 207–13; Westerman et al., "MassBridge," 40.

33. Westerman et al, "MassBridge," 46–47.

34. For a more detailed discussion of issues associated with online teaching and learning, see Bonvillian and Sarma, *Workforce Education*, 139–48. See also Sarma and Yoquinto, *Grasp*.

35. Sarma and Yoquinto, 47–48.

36. Westerman et al, "MassBridge," 44.

37. Bonvillian and Sarma, *Workforce Education*, 109–114.

38. The discussion here is drawn from Bonvillian and Sarma, *Workforce Education*, 127–29, 134–37.

39. Blivin and Mayo, "Shift Happens 2," 30.

CHAPTER 12

1. This chapter is drawn from Bonvillian, "Emerging Industrial Policies in the United States."

2. See, generally, Bonvillian and Singer, *Advanced Manufacturing*.

3. Hamilton, *The Works of Alexander Hamilton*, vol. 4.; Hamilton, *The Papers of Alexander Hamilton*, vol.10; National Academies of Sciences, Engineering, and Medicine, *Strategic Long-Term Participation*.

4. Smith, "George Washington"; Smith, *Harpers Ferry Armory*.

5. Summarized in Bonvillian and Singer, *Advanced Manufacturing*.

6. New Jersey Community Development Corporation, "What We Do"; Society for Establishing Useful Manufactures, "Prospectus."

7. See, for example, Stiles, *The First Tycoon*, 91–136.

8. Stiles, *The First Tycoon*, 438–73.

9. Bush, "Science, the Endless Frontier."

10. Warwick, "Beyond Industrial Policy"; see, generally, United Nations Conference on Trade and Development (UNCTAD), "Virtual Institute Teaching Material"; Page and Tarp, *The Practice of Industrial Policy*.

11. Atkinson, "Why the United States Needs a National Advanced Industry and Technology Agency."

12. A 2022 report from the Center for Strategic and International Studies explores some of the more traditional definitions of industrial policy; see DiPippo et al., "Red Ink."

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13. Mazzucato, Kattel, and Ryan-Collins, "Challenge-Driven Innovation Policy" 437; see also Mazzucato, *Mission Economy*.

14. See Atkinson, "Industrial Policy May Have Arrived: But for What?" Weller, Farooque, Govani, and Kaplan, in "Blinded by the Frontier," seek an industrial policy that will yield "hybrid learning tools and pedagogies to broaden access to high-quality education [and] energy technologies that align with communities' values and priorities, and [technology for] neglected and hazardous infrastructure" and argue that they are not pushing these goals "just for the sake of not losing scientific leadership to China"—which they seem to dismiss as technology saber-rattling, but because, as they ask, "[w]hat does outcompeting China in new technologies mean if we fail to advance American ideals of equality, justice, and opportunity?" Robertson and Hamilton, in "Economic Rights as Industrial Policy," argue that industrial policy should be reframed around economic interventions that benefit workers, prioritizing "child care, elder care, health care, and housing."

15. Tucker, "Industrial Policy and Planning."

16. Berger, "Back Down to Earth."

17. For a more detailed discussion of and citations to economists' perspectives on applications of industrial policy in East Asian economies and of more recent work on market failure justifications for industrial policies, see William B. Bonvillian, "Industrial Policies for the 21st Century: Lessons from the United States," United Nations Economic Commission for Latin America and the Caribbean (2024), 6–8, 10–12.

18. For a discussion of the dynamics of innovation, see Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 23–36, 181–96.

19. The detailed account of the four periods in chapter 4, of which this is a highly abbreviated version, is drawn from Bonvillian, "The New Model Innovation Agencies"; and Bonvillian, "Encompassing."

20. See, for example, Fong, "The Potential for Industrial Policy."

21. Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 165–66.

22. Lott, "Solyndra." Regarding industrial financing for Solyndra, see, generally, Lazonick, "There Went the Sun."

23. See, generally, Maher, "Manufacturing Our Way Back to Full Stock."

24. These events are detailed in Tooze, *Shutdown*, 79–154.

25. See Mandavilli, "New Infectious Threats." These new realities, which are not going away, include massive international travel, growing animal-human transmission, and widespread resistance to masking, vaccines, and other public health measures. Thus, public health experts predict that infectious outbreaks will grow in frequency and may become a new normal—exacerbated by chronic underfunding of public health systems, divided public health responsibilities between states, localities, and federal agencies, obsolete data collection systems, and a lack of urgency in making corrections.

26. Weiss and Bonvillian, *Structuring an Energy Technology Revolution*; Bonvillian, "Applying Innovation Policy to the U.S. Energy/Climate Challenge."

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27. See, for example, Naughton, *The Rise of China's Industrial Policy*.

28. Shin, "Global Value Chains under the Shadow of Covid," table 3.

29. Quoted in Adler, "Inside Operation Warp Speed."

30. Slaoui and Hepburn, "Developing Safe and Effective Covid Vaccines."

31. See, for example, Andrew Lo, MIT Sloan School, interview with Moderna CEO Stephane Bancel, April 20, 2020, https://www.youtube.com/watch?v=XvYiuoJ_lrI; Bourla, *Moonshot*; Miller, *The Vaccine*; Gelles, "The Husband-and-Wife Team."

32. Bonvillian, "Operation Warp Speed."

33. Adler, "Inside Operation Warp Speed."

34. US Department of Health and Human Services, Administration for Strategic Preparedness and Response, "Fact Sheet: $5 Billion 'Project NextGen' Initiative to Stay Ahead of COVID-19." May 11, 2023. https://aspr.hhs.gov/newsroom/Pages/ProjectNextGen-May2023.aspx.

35. Macrotrends, https://www.macrotrends.net/stocks/charts/TSLA/tesla/market-cap; Boudette, "Tesla."

36. Kane, "Tesla Production Sites."

37. See, generally, Vance, *Elon Musk*.

38. Tesla's loan from the Department of Energy was approved in 2009 and was available in January 2010; Tesla repaid the loan in 2013, ahead of schedule. See US Department of Energy, Loan Programs Office, "Tesla"; Higgins, *Power Play*, 109–12, 159, 169, 194. Also, communications to the author from Matt Hopkins, senior researcher, Academic-Industry Research Network, May 23, 2022.

39. Federal contracts from the National Aeronautics and Space Administration (NASA) beginning in 2008 enabled the survival of Musk's SpaceX company, which assisted his overall financial position in managing Tesla. See Majeed, "NASA 2008." Also, communications to the author from William Lazonick, professor of economics, University of Massachusetts Lowell, May 23, 2022.

40. Rezvani, "You Can Get a $7500 Tax Credit." The EV tax credit, initially created in the Energy Improvement and Extension Act of 2008 and later elaborated upon in the American Clean Energy and Security Act of 2009, was $7,500 for consumer purchases of EVs, limited to the first 200,000 cars produced by a firm. The 2022 Inflation Reduction Act provided a credit of $7,500 for vehicles assembled in the US, without the limit.

41. To access 2021 federal infrastructure funding, Tesla had to agree in 2021 to give up its proprietary changing system and shift to the Combined Charging System, the common standard for charging EVs. See Lambert, "Tesla Opening Supercharger Network." Also, communications to the author from Matt Hopkins, senior researcher, Academic-Industry Research Network, May 23, 2022.

42. See Boudette, "Tesla." Regulatory credits from other automakers to Tesla totaled $1.5 billion in 2021, making up 27 percent of its $5.5 billion in profits that year.

43. California Clean Vehicle Rebate Project, "CRVP Info: Eligibility & Requirements," https://cleanvehiclerebate.org/en/eligibility-guidelines.

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44. Hirsch, "Elon Musk's Growing Empire."

45. US Department of Energy (DOE), "DOE Announces $209 Million for Electric Vehicles Battery Research."

46. US Department of Energy (DOE), "Biden Administration, DOE to Invest $3 Billion."

47. Hansen, "The Inflation Reduction Act."

48. Jenkins, et al., *Preliminary Report*.

49. Service, "'Big Step Forward"; American Institute of Physics, "Billions for R&D."

50. This discussion is drawn from Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 120–21; that discussion draws on Deutch, "What Should the Government Do."

51. For a detailed discussion of government corporations, see Froomkin, "Reinventing the Government Corporation."

52. See, for example, Hwang et al., "Symbiosis of Semiconductors."

53. Greg Slater, vice president of Intel, American Technology Leadership Is Critical to Semiconductor Supply Chain Resiliency, *Intel Blog*, June 8, 2021, https://blogs.intel.com/policy/2021/06/08/american-technology-leadership-is-critical-to-semiconductor-supply-chain-resiliency/#gs.8t4ndh.

54. See, generally, Johnson, *MITI and the Japanese Miracle*.

55. Browning and Shetler, *Sematech*.

56. Jie, Yang, and Fitch, "The World Relies"; Miller, *The Chip War*, 209–20.

57. Semiconductor Industry Association, "Semiconductor 2019 Factbook."

58. Van Sloun, "U.S. Investment in Semiconductor Manufacturing."

59. Triolo, "The Future"; Strub, "China's Innovation Policy and the Quest for Semiconductor Autonomy"; Ernst, "China's Bold Strategy for Semiconductors."

60. Griffith and Goguichvili, "The U.S. Needs a Sustained, Comprehensive, and Cohesive Semiconductor National Security Effort."

61. Hunt, "Sustaining U.S. Competitiveness in Semiconductor Manufacturing."

62. White House, "Building Resilient Supply Chains."

63. Federal Consortium for Advanced Batteries, "National Blueprint for Lithium Batteries 2021–2030."

64. CHIPS for America Act, S.3933; see also Warner, "Bipartisan, Bicameral Bill."

65. White House, "The Biden-Harris Plan to Revitalize American Manufacturing and Secure Critical Supply Chains in 2022."

66. Atkinson, "Why the United States," 1–3.

67. S. 3832, Endless Frontier Act, 116th Cong. 2nd Sess., introduced May 21, 2020, https://www.congress.gov/bill/116th-congress/senate-bill/3832/text; Young, "Young, Schumer Unveil Endless Frontier Act."

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68. S.1260, U.S. Innovation and Competition Act of 2021, introduced on April 20, 2021, https://www.congress.gov/bill/117th-congress/senate-bill/1260.

69. HR 2225 National Science Foundation for the Future Act, 17th congress, 1st Sess., March 26, 2021, https://www.congress.gov/bill/117th-congress/house-bill/2225; House Committee on Science, Space and Technology, summary of HR 2225, NSF for the Future Act, and of HR 3593, DOE Science for the Future Act, https://housesciencecommittee.medium.com.

70. HR 4346, The CHIPS and Science Act of 2022, 117th Cong. 2nd Sess., July 29, 2022, bill text, and Section-by-Section Summary prepared by the Senate Committee on Commerce Science and Transportation, https://www.commerce.senate.gov/2022/8/view-the-chips-legislation; Senate Committee on Commerce Science and Transportation, CHIPS and Science Act, Section-by-Section Summary and Division B Summary, https://www.commerce.senate.gov/services/files/1201E1CA-73CB-44BB-ADEB-E69634DA9BB9.

71. Council of Social Science Associations (COSSA), CHIPS and Science Act, Section-by-Section Summary, August 19. 2022, https://cossa.org/wp-content/uploads/2022/08/CHIPS-and-Science-Act-Section-by-Section-2022.pdf.

72. Senate Commerce Committee, Division B Summary.

73. Senate Commerce Committee, Section-by-Section and Division B Summary.

74. Lopez, "How Congress Wrecked its Own Science Bill"; Hammond, "How Congress Ruined the Endless Frontier Act."

75. Discussion here draws from Bonvillian, "Testimony."

76. See, for example, Atkinson, Muro and Whiton, "The Case for Growth Centers"; Gruber and Johnson, *Jump-Starting America*.

77. Porter, "Clusters and the New Economics of Competition"; for a summary of limitations in the theory, see, for example, Motoyama, "What Was New About Cluster Theory?"

78. Armstrong, "Brass Cities."

79. Armstrong, "Industrial Policy and Local Economic Transformation."

CHAPTER 13

1. See, for example, US Department of Defense (DOD), "DMEA Trusted IC Program"; see also Lapedus, "A Crisis"; Ortiz, "Microelectronics in Defense Systems"; US Department of the Air Force, Office of the Chief Scientist, NDAA 2023 Mandated Independent Review of USD (R&E) Microelectronics Quanltifiable Assurance Effort.

2. DARPA Electronics Resurgence Initiative, https://www.darpa.mil/work-with-us/electronics-resurgence-initiative.

3. Compare U.S. Department of Defense (DOD), "The Microelectronics Commons: A National Network of Prototyping Innovation Hubs," with National Institute of Standards and Technology (NIST), "CHIPS for America Outlines Vision for the National Semiconductor Technology Center."

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4. Compare Defense Advanced Research Projects Agency (DARPA), "Next Generation Microelectronics Manufacturing Program Announcement," and Defense Advanced Research Projects Agency (DARPA), "Next Generation Microelectronics Manufacturing Aims to Sustain R&D Ecosystem," with National Institute of Standards and Technology (NIST), "The Vision for the National Advanced Packaging Manufacturing Program."

5. White House, "National Science and Technology Council," n.d., https://www.whitehouse.gov/ostp/nstc/.

6. DiPippo et al., "Red Ink," 2.

7. DiPippo et al., "Red Ink," 14.

8. DiPippo et al., "Red Ink," 12.

9. This section draws on Adler, "Guiding Finance."

10. Adler, "Guiding Finance"; Organisation for Economic Cooperation and Development (OECD), "Measuring Distortions."

11. See, for example, Jing, "China's Tech Pivot"; Liao, "China Tech Roundup"; McGregor, "China's Tech Crackdown."

12. Naughton, *The Rise of China's Industrial Policy*, 117.

13. Naughton, *The Rise of China's Industrial Policy*; Rithmire, "The Resurgent Role of the State."

14. Rithmire, "The Resurgent Role of the State"; Adler, "Guiding Finance."

15. Lapedus, "China Accelerates Foundry."

16. White House, "Building Resilient Supply Chains," 68.

17. See Molnar, "Advanced Manufacturing Strategy." Michael Molnar is the NIST Advanced Manufacturing National Program Office director.

18. See, for example, Ramadan, "Narrowing the Gap."

19. Yang, "How Did China Come to Dominate the World of Electric Cars?"

20. Root, "Tesla and BYD Are Beating Their EV Rivals in China."

21. Harley, "China Overtakes Japan."

22. The role of change agents in innovation is discussed in Bonvillian and Weiss, *Technological Innovation in Legacy Sectors,* 186–88, 213–14.

23. See, generally, Bonvillian, Van Atta, and Windham, *The DARPA Model*.

24. US Census Bureau, https://www.census.gov/foreign-trade/balance/c0007.html.

25. Adler and Bonvillian, "America's Advanced Manufacturing Problem."

26. Hart, "Building Back Cleaner."

27. Coons, "Sen. Coons, Colleagues Seek to Create New Domestic Manufacturing Investment Corporation."

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

28. White House, "Statement by National Security Advisor Jake Sullivan and Economic Council Director Brian Deese."

29. See, for example, Robyn, "Mission, Money, and Process Makeover."

30. Vonortas, "Innovation and Public Procurement in the United States."

31. National Network for Critical Technology Assessment, "Securing America's Future, A Framework for Critical Technology Assessment."

CHAPTER 14

1. Sekar, "National Institutes of Health (NIH) Funding: FY1996–FY2023," 9.

2. The organizational model of the Howard Hughes Medical Institute, the second-largest US philanthropic organization, was in some ways a response to these NIH issues, including its focus on larger-scale support for leading researchers pursuing specific, long-range breakthrough areas and its interdisciplinary approach. See https://www.hhmi.org/programs/biomedical-research.

3. Bonvillian and Singer, *Advanced Manufacturing*, 102–28.

4. Pacala and Socolow, "Stabilization Wedges."

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

BIBLIOGRAPHY

Abernathy, William J., and James M. Utterback. "Patterns of Innovation in Technology." *Technology Review* 80, no. 7 (June/July 1978): 40–47.

Activate, "The World Needs Scientists More Than Ever," https://www.activate.org/mission.

Adams, Sean Patrick. *Home Fires: How Americans Kept Warm in the 19th Century*. Baltimore: Johns Hopkins University Press, 2014.

Adler, David. "Guiding Finance: China's Strategy for Funding Advanced Manufacturing." *American Affairs* VI, no. 2 (2022): 17–43. https://americanaffairsjournal.org/2022/05/guiding-finance-chinas-strategy-for-funding-advanced-manufacturing/.

Adler, David. "Inside Operation Warp Speed: A New Model for Industrial Policy." *American Affairs* 5, no. 2 (2021): 3–32.

Adler, David, and William B. Bonvillian. "America's Advanced Manufacturing Problem—and How to Fix It." *American Affairs* 7, no. 3 (2023): 3–30. https://americanaffairsjournal.org/2023/08/americas-advanced-manufacturing-problem-and-how-to-fix-it.

Advanced Manufacturing Partnership. "Report to the President: Accelerating U.S. Advanced Manufacturing." 2014. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf.

Advanced Manufacturing Partnership. "Report to the President on Ensuring American Leadership in Advanced Manufacturing." Executive Office of the President. June 2011. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

Advanced Research and Invention Agency (ARIA). "Policy Statement." March 19, 2021. https://www.gov.uk/government/publications/advanced-research-and-invention-agency-aria-statement-of-policy-intent/advanced-research-and-invention-agency-aria-policy-statement.

Alic, John A., Lewis M. Branscomb, Harvey Brooks, and Ashton B. Carter. *Beyond Spinoff: Military and Commercial Technologies in a Changing World*. Cambridge, MA: Harvard Business School Press, 1992.

Alic, John A., Daniel Sarewitz, Charles Weiss, and William B. Bonvillian. "A New Strategy for Energy Innovation." *Nature* 466, no. 7304 (2010): 316–17.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Alvarez, Luis W. "Alfred Lee Loomis." In *Biographical Memoirs, vol. 51*. Washington, DC: National Academy of Sciences, 1980. http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/loomis-alfred.pdf.

American Institute of Physics. "Billions for R&D Included in Senate-Passed Infrastructure Bill and Reconciliation Blueprint." American Institute of Physics, *FYI Bulletin* 75, August 13, 2021. https://ww2.aip.org/fyi/2021/billions-rd-included-senate-passed-infrastructure-bill-and-reconciliation-blueprint.

Armstrong, Ben B. D. "Brass Cities: Innovation Policy and Local Economic Transformation." PhD diss., Massachusetts Institute of Technology, Cambridge, MA, 2019.

Armstrong, Ben. "Industrial Policy and Local Economic Transformation: Evidence from the U.S. Rust Belt." *Economic Development Quarterly* 35, no. 3 (2021): 181–196.

Armstrong, Benjamin, William B. Bonvillian, and Suzanne Berger. "Advanced Technology, Advanced Training: A New Policy Agenda for U.S. Manufacturing." Cambridge, MA: Initiative for Knowledge and Innovation in Manufacturing, 2021.

Athanasia, Gabrielle, and Jillian Cota. "The U.S. Should Strengthen STEM Education to Remain Globally Competitive." Center for Strategic and International Studies (CSIS), Washington, DC, April 1, 2022. https://www.csis.org/blogs/perspectives-innovation/us-should-strengthen-stem-education-remain-globally-competitive.

Atkinson, Robert D. "Industrial Policy May Have Finally Arrived: But for What?" *Information Technology & Innovative Foundation*, November 16, 2020. https://itif.org/publications/2020/11/16/industrial-policy-may-have-finally-arrived-what/.

Atkinson, Robert D. *The Past and Future of America's Economy*. Cheltenham, UK: Edward Elgar Publishing, 2004.

Atkinson, Robert D. "Potato Chips, Computer Chips: Yes, There Is a Difference." *American Compass*, December 23, 2020. https://americancompass.org/the-commons/potato-chips-computer-chips-yes-there-is-a-difference/.

Atkinson, Robert D. "Understanding the U.S. National Innovation System, 2020." *Information Technology & Innovation Foundation*, November 2, 2020. https://itif.org/publications/2020/11/02/understanding-us-national-innovation-system-2020.

Atkinson, Robert D. "U.S. Manufacturing Productivity Is Falling and It's a Cause for Alarm." *Industry Week*, July 12, 2021. https://www.industryweek.com/the-economy/article/21169426/falling-us-manufacturing-productivity-is-cause-for-alarm.

Atkinson, Robert D. "Why the United States Needs a National Advanced Industry and Technology Agency." *Information Technology & Innovation Foundation*, June 17, 2021. https://itif.org/publications/2021/06/17/why-united-states-needs-national-advanced-industry-and-technology-agency/.

Atkinson, Robert D., and Darrene Hackler, "Economic Doctrines and Approaches to Climate Change Policy." *Information and Innovation Technology Foundation*, October 2010. http://www.itif.org/files/2010-econ-climate-change.pdf.

Atkinson, Robert, Mark Muro, and Jacob Whiton. *The Case for Growth Centers*. Washington, DC: Brookings Institution and Information Technology & Innovation Foundation, 2019. https://www.brookings.edu/research/growth-centers-how-to-spread-tech-innovation-across-america/.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Atkinson, Robert D., Luke A. Stewart, Scott Andes, and Stephen Ezell. "Worse Than the Great Depression: What Experts Are Missing About American Manufacturing Decline." *Information Technology and Innovation Foundation,* March 19, 2012.

Audretsch, David B. *Why Is Germany So Strong in Manufacturing?* Bloomington: University of Indiana Manufacturing Policy Initiative, March 2018. https://policyinstitute.iu.edu/doc/mpi/insight/2018-03.pdf.

Autor, David H. "Trade and Labor Markets: Lessons from China's Rise." *IZA World of Labor*, February 2018.

Autor, David H., David Dorn, and Gordon H. Hanson. "The China Shock: Learning from Labor-Market Adjustment to Large Change in Trade." *Annual Review of Economics* 8 (2016): 205–240.

Autor, David H., David Dorn, and Gordon H. Hanson. *On the Persistence of the China Shock*. National Bureau of Economic Research, Cambridge, MA. 2021. https://www.brookings.edu/bpea-articles/on-the-persistence-of-the-china-shock/.

Autor, David, David Dorn, Gordon H. Hanson, Gary Pisano, and Pian Shu. "Foreign Competition and Domestic Innovation: Evidence from U.S. Patents." NBER Working Paper 22879. Cambridge, MA: National Bureau of Economic Research, 2016.

Autor, David, Arindrajit Dube, and Annie McGrew. "Unexpected Compression: Competition at Work in the Low Wage Labor Market." NBER Working Paper 31010. National Bureau of Economic Research, Cambridge, MA, November 2023. https://shapingwork.mit.edu/wp-content/uploads/2023/11/Autor_Dube_McGrew_Nov-2023.pdf.

Bancel, Stéphane. "The First COVID-19 Vaccine in the Clinic: A Lecture with Stéphane Bancel, CEO of Moderna." Interview by Andrew Lo. April 2, 2020. Video, 1:28:07. https://www.youtube.com/watch?v=XvYiuoJ_lrI.

Bancel, Stéphane. "Moderna's Path to Vaccine Innovation: A Talk with CEO Stéphane Bancel." Interview by Olivier Leclerc. McKinsey & Company, Waltham, MA, August 27, 2021. https://www.mckinsey.com/industries/life-sciences/our-insights/modernas-path-to-vaccine-innovation-a-talk-with-ceo-stephane-bancel.

Bayh, Birch, Joseph P. Allen, and Howard W. Bremer, "Universities, Inventors and the Bayh Dole Act." *Life Sciences Law and Industry Report* 3, no. 24 (2009): 1–5.

Beahm, George. *I, Steve: Steve Jobs in His Own Words*. Evanston, IL: Agate Publishing, 2011.

Becker, Gary S. *Human Capital: A Theoretical and Empirical Analysis, with Special Reference to Education*. Chicago: University of Chicago Press, 1964.

Bell, Charles. *The Hand: Its Mechanism and Vital Endowments, as Evincing Design*. London: Bell & Daldy, 1865.

Benen, Steve. "Departing NIH Chief Eyes More Research 'On Human Behavior.'" *MaddowBlog*, December 21, 2021. https://www.msnbc.com/rachel-maddow-show/maddowblog/departing-nih-chief-eyes-more-research-human-behavior-n1286390.

Bennis, Warren, and Patricia Ward Biederman. *Organizing Genius: The Secrets of Creative Collaboration*. New York: Basic Books, 1997.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Bergen, Mark. "The Investors Putting Billions Into Climate Tech Don't Plan to Stop Now." *Bloomberg*, June 17, 2022. https://www.bloomberg.com/news/articles/2022-06-17/climate-tech-investors-advise-the-boom-is-here-to-stay.

Berger, Suzanne. "Back Down to Earth." *Boston Review*, September 15, 2021. https://bostonreview.net/forum_response/back-down-to-earth/.

Berger, Suzanne. "Globalization Survived Populism Once Before—and It Can Again." *Boston Review*, February 2018. https://bostonreview.net/articles/suzanne-berger-globalization-survived-populism/.

Berger, Suzanne. "How the Financial Sector Gutted Manufacturing." *Boston Review*, March 1, 2014. https://bostonreview.net/forum/suzanne-berger-finance-gutted-manufacturing/.

Berger, Suzanne. *How We Compete: What Companies Around the World Are Doing to Make It in Today's Global Economy*. New York: Currency, 2005.

Berger, Suzanne. *Making in America: From Innovation to Market*. Cambridge, MA: MIT Press, 2013.

Berlin, Leslie. *The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley*. New York: Oxford University Press, 2005.

Bhagwati, Jagdish. "The Computer Chip vs. Potato Chip Debate." *Moscow Times*, September 1, 2010. https://www.themoscowtimes.com/2010/09/01/the-computer-chip-vs-potato-chip-debate-a1075.

Biden, Joseph R. "Remarks by President Biden in Address to a Joint Session of Congress." Washington, DC, April 28, 2021. https://www.whitehouse.gov/briefing-room/speeches-remarks/2021/04/29/remarks-by-president-biden-in-address-to-a-joint-session-of-congress/.

Bird, Kai, and Martin J. Sherwin. *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer*. New York: Vintage Books, 2006.

Blanpied, William A. "Inventing US Science Policy." *Physics Today* 51, no. 2 (1998): 34–40. https://www.nsf.gov/about/history/nsf50/science_policy.jsp.

Blivin, Jamai, and Merrilea Mayo. *Shift Happens 2: Finding Strong Footing: The Future of Assessment in the Learning-to-Employment Landscape*. Santa Fe, NM: Innovate + Educate, 2019. https://innovate-educate.org/wp-content/uploads/2017/04/ShiftHappens2.pdf.

Bloomberg New Energy Financing. "Energy Transition Investment Trends 2022." *Bloomberg*, January 2022. https://assets.bbhub.io/professional/sites/24/Energy-Transition-Investment-Trends-Exec-Summary-2022.pdf.

Bonvillian, William B. "Advanced Manufacturing and the Construction Sector." Presentation to the Advanced Building Construction Collaborative, Washington, D.C., April 29, 2021.

Bonvillian, William B. "Advanced Manufacturing Policies and Paradigms for Innovation." *Science* 342, no. 6163 (2013): 1173–75. http://www.sciencemag.org/content/342/6163/1173.full.

Bonvillian, William B. "All That DARPA Can Be." *American Interest* 11, no. 1 (2015).

Bonvillian, William B. "Applying Innovation Policy to the U.S. Energy/Climate Challenge." Chapter 12 in *Delivering Energy Law and Policy in the EU and US,* edited by Raphael Heffron and Gavin Little. Edinburgh: Edinburgh University Press, 2016.

Bonvillian, William B. "The ARPA Model—U.S. Lessons for ARIA." Presentation at the Conference on Next Steps for the Advanced Research and Innovation Agency of the Westminster Higher Education Forum, February 25, 2022.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Bonvillian, William B. "The Connected Science Model for Innovation—The DARPA Role." In *21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change*. Washington, DC: National Academies Press, 2009.

Bonvillian, William B. "DARPA and Its ARPA-E and IARPA Clones: A Unique Innovation Organization Model." *Industrial and Corporate Change* 27, no. 5 (2018): 897–914.

Bonvillian, William B. "DOD's Role in Energy Innovation." *Issues in Science and Technology* 31, no. 2 (2015): 10–14.

Bonvillian, William B. "Donald Trump's Voters and the Decline of American Manufacturing." *Issues in Science and Technology* 32, no. 4 (2016): 27.

Bonvillian, William B. "Emerging Industrial Policies in the United States." *ITIF Report*, October 4, 2021. https://itif.org/publications/2021/10/04/emerging-industrial-policy-approaches-united-states.

Bonvillian, William B. "Encompassing the Innovation Panoply." *Issues in Science and Technology* 38, no. 2 (2022): 37–43.

Bonvillian, William B. "Ensuring Manufacturing USA Reaches Its Potential." *Day One Project*, August 2021. https://www.dayoneproject.org/post/ensuring-manufacturing-usa-reaches-its-potential.

Bonvillian, William B. "Industrial Policies for the 21st Century: Lessons from the United States." United Nations Economic Commission for Latin America and the Caribbean (2024).

Bonvillian, William B. "The New Model Innovation Agencies: An Overview." *Science and Public Policy* 41, no. 4 (2014): 425–37.

Bonvillian, William B. "Operation Warp Speed: Harbinger of American Industrial Innovation Policies." *Science and Public Policy* (2024).

Bonvillian, William B. "Restoring U.S. Leadership in Manufacturing." *Day One Project*, January 23, 2020. https://www.dayoneproject.org/post/restoring-u-s-leadership-in-manufacturing.

Bonvillian, William B. "Testimony to the U.S. Senate Committee on Commerce, Science, and Transportation at the Hearing on the 'Endless Frontier Act.'" April 14, 2021. https://www.commerce.senate.gov/services/files/0DAF8ACC-8382-4E85-BEBA-1F8B5F577922.

Bonvillian, William B., and Sanjay E. Sarma. *Workforce Education: A New Roadmap*. Cambridge, MA: MIT Press, 2021.

Bonvillian, William B., and Peter L. Singer. *Advanced Manufacturing: The New American Innovation Policies*. Cambridge, MA: MIT Press, 2018.

Bonvillian, William B., and Peter L. Singer. "What Economists Don't Know About Manufacturing." *American Interest* 13, no. 5 (2018):17–23.

Bonvillian, William B., and Richard Van Atta. "ARPA-E and DARPA: Applying the DARPA Model to Energy Innovation." *Journal of Technology Transfer* 36, no. 5 (2011) 469–513.

Bonvillian, William B., Richard Van Atta, and Patrick Windham. *The DARPA Model for Transformative Technologies: Perspectives on the U.S. Defense Advanced Research Projects Agency*. Oxford, UK: Open Book Publishers, 2019.

Bonvillian, William B., and Charles Weiss. "Taking Covered Wagons East: A New Innovation Theory for Energy and Other Legacy Sectors." *Innovations: Technology, Governance, Globalization* 4, no. 4 (2009): 289–300.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Bonvillian, William B., and Charles Weiss. *Technological Innovation in Legacy Sectors*. New York: Oxford University Press, 2015.

Borrell, Brendan. *The First Shots: The Epic Rivalries and Heroic Science behind the Race to the Coronavirus Vaccine*. Boston: Mariner Books, 2021.

Boucher, Helen W. "Bad Bugs, No Drugs 2002–2020: Progress, Challenges, and Call to Action." *Transactions of the American Clinical and Climatological Association* 131 (2020): 65.

Boucher, Helen W., George H. Talbot, John S. Bradley, et al. "Bad Bugs, No Drugs: No ESKAPE! An Update from the Infectious Diseases Society of America." *Clinical Infectious Diseases* 48, no. 1 (2009): 1–12.

Boudette, Neal E. "Tesla Reports Record Yearly Profit But Warns That Supply Problems Persist." *New York Times*, January 26, 2022. https://www.nytimes.com/2022/01/26/business/tesla-earnings.html.

Bourla, Albert. *Moonshot: Inside Pfizer's Nine-Month Race to Make the Impossible Possible*. New York: HarperCollins, 2022.

Branscomb, Lewis M., and Philip E. Auerswald. *Between Invention and Innovation—An Analysis of Funding for Early-Stage Technology Development*. NIST Report GRC 02-84. Washington, DC: United States Department of Commerce, 2002. https://www.nist.gov/system/files/documents/2017/05/09/gcr02-841.pdf.

Branscomb, Lewis M., and Philip E. Auerswald. *Taking Technical Risks: How Innovators, Executives, and Investors Manage Risks in High-Tech Innovations*. Cambridge, MA: MIT Press, 2003.

Branswell, Helen. "Kizzmekia Corbett on the Pandemic, Public Service, and Her Path to Becoming a Scientist." *STAT*, April 18, 2022. https://www.statnews.com/2022/04/18/kizzmekia-corbett-scientist-pandemic/.

Breznitz, Dan, and Michael Murphree. *Run of the Red Queen: Government, Innovation, Globalization, and Economic Growth in China*. New Haven, CT: Yale University Press, 2011.

Browning, Larry D., and Judy C. Shetler. *Sematech: Saving the U.S. Semiconductor Industry*. College Station: Texas A&M University Press, 2000.

Buderi, Robert. *The Invention That Changed the World: How a Small Group of Radar Pioneers Won the Second World War and Launched a Technical Revolution*. New York: Simon & Schuster, 1996.

Buderi, Robert. *Where Futures Converge: Kendall Square and the Making of a Global Innovation Hub*. Cambridge, MA: MIT Press, 2022.

Bureau of Labor Statistics, "Industries at a Glance," https://www.bls.gov/iag/tgs/iag31-33.htm.

Bureau of Labor Statistics, "Monthly Labor Review," https://www.bls.gov/opub/mlr/2018/article/multifactor-productivity-slowdown-in-us-manufacturing.htm.

Bush, Vannevar. *Science, the Endless Frontier: A Report to the President on a Program for Postwar Scientific Research*. Washington, DC: U.S. Government Printing Office, 1945. https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm.

California Clean Vehicle Rebate Project, "CRVP Info: Eligibility & Requirements," https://cleanvehiclerebate.org/en/eligibility-guidelines.

Carbon Mitigation Initiative, High Meadows Environmental Institute, Princeton University. "Stabilization Wedges Slides and Graphics." 2000. https://cmi.princeton.edu/wp-content/uploads/2020/01/Wedges_Figure2_8-scaled.jpg.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Carleton, Tammy L. "The Value of Vision in Technological Innovation." PhD diss., Stanford University, 2010.

Centers for Disease Control and Prevention (CDC). "What Is *C. diff*?" September 7, 2022. https://www.cdc.gov/cdiff/what-is.html.

Centers for Medicare and Medicaid Services. "National Health Expenditure Accounts (NHEA)." https://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/NationalHealthExpendData/NationalHealthAccountsHistorical/.

Chernow, Ron. *Titan: The Life of John D. Rockefeller, Sr*. New York: Vintage, 2004.

Chposky, James, and Ted Leonsis. *Blue Magic: The People, Power and Politics Behind the IBM Personal Computer*. New York: Facts on File, 1988.

Christensen, Clayton M. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Cambridge, MA: Harvard Business Review Press, 1997.

Clark, Corrie E. "Renewable Energy R&D Funding History: A Comparison with Funding for Nuclear Energy, Fossil Energy, Energy Efficiency, and Electric Systems R&D." *Congressional Research Service*, June 18, 2018. https://sgp.fas.org/crs/misc/RS22858.pdf.

Cohen, Jon. "The United States Badly Bungled Coronavirus Testing—But Things May Soon Improve." *Science*, February 28, 2020. https://www.science.org/content/article/united-states-badly-bungled-coronavirus-testing-things-may-soon-improve.

Collins, Francis S., Tara A. Schwetz, Lawrence A. Tabak, and Eric S. Lander. "ARPA-H: Accelerating Biomedical Breakthroughs." *Science* 373, no. 6651 (2021): 165–67.

Commission on Health Research for Development. *Health Research: Essential Link to Equity in Development*. New York: Oxford University Press, 1990.

Committee for a Responsible Federal Budget. "American Health Care: Health Care Spending and the Federal Budget." May 16, 2018. https://www.crfb.org/papers/american-health-care-health-spending-and-federal-budget.

Community College Research Center. "Community College FAQs." https://ccrc.tc.columbia.edu/community-college-faqs.html.

Conant, Jennet. *109 East Palace: Robert Oppenheimer and the Secret City of Los Alamos*. New York: Simon & Schuster, 2005.

Conant, Jennet. *Tuxedo Park: A Wall Street Tycoon and the Secret Palace of Science That Changed the Course of World War II*. New York: Simon & Schuster, 2003.

Congressional Research Service. "'Made in China 2025' Industrial Policies: Issues for Congress. *In Focus*, August 11, 2020 (updated December 22, 2022). https://fas.org/sgp/crs/row/IF10964.pdf.

Converged. "American Manufacturing Statistics." https://www.propelplm.com/blog/american-manufacturing-statistics.

Cook-Deegan, Robert Mullan. "The Alta Summit, December 1984." *Genomics* 5, no. 3 (1989): 661–63.

Cook-Deegan, Robert Mullan. "Does NIH Need a DARPA?" *Issues in Science and Technology* 13, no. 2 (1996): 25–28. https://issues.org/national-institutes-health-nih-darpa-cook-deegan/.

Cook-Deegan, Robert Mullan. *The Gene Wars: Science, Politics and the Human Genome*. New York: W. W. Norton & Company, 1994.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Cook-Deegan, Robert Mullan. "Origins of the Human Genome Project." *Risk* 5 (1994): 97.

Coons, Chris. "Sen. Coons, Colleagues Seek to Create New Domestic Manufacturing Investment Corporation." Press release, August 12, 2021. https://www.coons.senate.gov/news/press-releases/sen-coons-colleagues-seek-to-create-new-domestic-manufacturing-investment-corporation.

Cooper, Robert G., Scott J. Edgett, and Elko J. Kleinschmidt. "Optimizing the Stage-Gate Process: What Best-Practice Companies Do." *Research-Technology-Management* 45 no. 5 (2002): 21–27.

Corporate Finance Institute. "Kondratieff Wave." December 20, 2022. https://corporatefinanceinstitute.com/resources/economics/kondratieff-wave/.

Council of Economic Advisors (US). "Active Labor Market Policies: Theory and Evidence for What Works." Washington, DC: Council of Economic Advisors, Washington, DC, December 2016. https://obamawhitehouse.archives.gov/sites/default/files/page/files/20161220_active_labor_market_policies_issue_brief_cea.pdf.

Council of Economic Advisers (US). "Addressing America's Reskilling Challenge." Council of Economic Advisers, Washington, DC, July 2018. https://www.trumpwhitehouse.archives.gov/wp-content/uploads/2018/07/Addressing-Americas-Reskilling-Challenge.pdf.

Council of Economic Advisers (US). "Economic Report of the President, Transmitted to the Congress February 2016 Together with the Annual Report of the Council of Economic Advisers." Council of Economic Advisers, Washington, DC, 2016. https://www.govinfo.gov/content/pkg/ERP-2016/pdf/ERP-2016.pdf.

"Crafting Policy for the Information Age: EU Research on Intangibles." *The Intangible Economy*, October 16, 2003. https://intangibleeconomy.wordpress.com/2003/10/.

Crichton, Michael. *The Andromeda Strain*. New York: Alfred A. Knopf, 1969.

Cunliffe, Colin. "Energy Innovation in the FY 2021 Budget: Congress Should Lead." *Information Technology and Innovation Foundation*, 2020. https://itif.org/publications/2020/03/30/energy-innovation-fy-2021-budget-congress-should-lead/.

Cyclotron Road. "About Us," https://cyclotronroad.lbl.gov/about-us.

Cyclotron Road. "Activating Tomorrow's Technology Leaders: How Cyclotron Road's Entrepreneurial Fellowships Are Bridging the Science-to-Product Gap." 2018. https://cyclotronroad.lbl.gov/sites/default/files/2021-05/33637%20Cyclotron%20Road%20Impact%20Report.pdf.

Defense Advanced Research Projects Agency (DARPA). "DARPA: Bridging the Gap Powered by Ideas." Report ADA 433949. February 2005. https://archive.org/details/DARPA—Bridging-The-Gap-Powered-By-Ideas—2005/page/n1/mode/2up.

Defense Advanced Research Projects Agency (DARPA). *DARPA over the Years*. Arlington, VA: DARPA, 2003.

Defense Advanced Research Project Agency (DARPA). "Next Generation Microelectronics Manufacturing Aims to Sustain R&D Ecosystem." July 20, 2023. https://www.darpa.mil/news-updates/2023-07-20.

Defense Advanced Research Projects Agency (DARPA). "Next Generation Microelectronics Manufacturing (NGMM) Program Announcement." November 21, 2023, https://www.darpa.mil/news-events/2023-11-17.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Denison, Edward. *Trends in American Economic Growth, 1929–1982*. Washington, DC: Brookings Institution Press, 1985.

Deutch, John. *What Should the Government Do to Encourage Technical Change in the Energy Sector?* Report No. 120. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change, 2005. https://dspace.mit.edu/handle/1721.1/18089.

Dewey, John. *Education and Experience*. New York: Macmillan, 1938.

Dieter, Ernst. "China's Bold Strategy for Semiconductors–Zero-Sum Game or Catalyst for Cooperation?" East-West Center Working Papers Innovation and Economic Growth Series 9, 2016.

DiMasi, Joseph A., Henry G. Grabowski, and Ronald W. Hansen. "Innovation in the Pharmaceutical Industry: New Estimates of R&D Costs." *Journal of Health Economics* 47 (2016): 22–33.

DiPippo, Gerard, Ilaria Mazzocco, Scott Kennedy, and Matthew P. Kennedy. *Red Ink: Estimating Chinese Industrial Policy Spending in Comparative Perspective*. Washington, DC: Center for Strategic and International Studies, 2022, https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/220523_DiPippo_Red_Ink.pdf.

Dolgin, Elie. "How COVID Unlocked the Power of RNA Vaccines." *Nature* 589, no. 7841 (2021): 189–192.

Dolgin, Elie. "The Tangled History of mRNA Vaccines." *Nature* 597, no. 7876 (2021): 318–324.

Domar, Evsey D. "Capital Expansion, Rate of Growth and Employment." *Econometrics* 14, no. 2 (April 1946): 137–147.

Dosi, Giovanni, Mariacristina Piva, Maria Enrica Virgillito, and Marco Vivarelli. "Embodied and Disembodied Technological Change: The Sectoral Patterns of Job-creation and Job-destruction." *Research Policy* 50, no. 4 (2021): 104199.

Drexler, K. Eric. *Engines of Creation: The Coming Era of Nanotechnology*. New York: Anchor Books, 1985.

Drexler, K. Eric. "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation." *Proceedings of the National Academy of Sciences* 78, no. 9 (1981): 5275–78.

Economic Policy Institute. "U.S. Trade Deficits Hit Record Highs in 2021." https://www.epi.org/blog/u-s-trade-deficits-hit-record-highs-in-2021-more-effective-trade-industrial-and-currency-policies-are-needed-to-create-more-domestic-manufacturing-jobs/.

The Economist. "A Growing Number of Governments Hope to Clone America's DARPA." June 3, 2021. https://www.economist.com/science-and-technology/2021/06/03/a-growing-number-of-governments-hope-to-clone-americas-darpa.

Education Trust. "Core Problems: Out-of-Field Teaching Persists in Key Academic Courses and High-Poverty Schools." Washington, DC: Education Trust, November 2008.

Ehlers, Vernon. *Unlocking Our Future: Toward a New National Science Policy*. Report prepared for the use of the Committee on Science, 105th Cong. 1998. Committee Print 105-B. https://www.aaas.org/sites/default/files/s3fs-public/GPO-CPRT-105hprt105-b.pdf.

Elliott, Vittoria. "Twitter Really Is Worse than Ever." Wired, May 3, 2023. https://www.wired.com/story/twitter-really-is-worse-than-ever/#:~:text=Under%20Elon%20Musk%2C%20hate%20

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

speech,and%20propaganda%20accounts%20have%20thrived.&text=A%20year%20ago%2C%20Elon%20Musk,place%20for%20unfettered%20free%20speech.

Engelbart, Doug. "The Mother of All Demos." YouTube video, 1:40:52. 1968. https://www.youtube.com/watch?v=yJDv-zdhzMY.

The Engine. "The Engine Expansion." October 2022. https://www.engine.xyz/wp-content/uploads/2021/09/The_Engine_Expansion_Overview_8_21.pdf.

The Engine, Built by MIT. "About Us." https://www.engine.xyz/about-us/our-mission/.

Ericsson, K. Anders, Robert R. Hoffman, Aaron Kozbelt, and A. Mark Williams, eds. *Cambridge Handbook of Expertise and Expert Performance*. 2nd ed. Cambridge: Cambridge University Press, 2013.

Ericsson, K. Anders, Michael J. Prietula, and Edward T. Cokely. "The Making of an Expert." *Harvard Business Review* 85, no. 7/8 (2007): 114. https://hbr.org/2007/07/the-making-of-an-expert.

Estes, Adam Clark. "DARPA's Very Expensive, Sci-Fi Projects from the Future." *The Atlantic*, August 18, 2011. https://www.theatlantic.com/technology/archive/2011/08/darpas-very-expensive-sci-fi-projects-future/354282/.

Eustace, Clark. "The Intangible Economy: Overview of PRISM Research Findings." In *The Economic Importance of Intangible Assets*, edited by Patrizio Bianchi and Sandrine Labory. London: Routledge, 2004.

Evans, Sir Harold. *They Made America*. Sloan Foundation Project. Little Brown, 2005.

Fauci, Anthony S. "Biodefence on the Research Agenda." *Nature* 421, no. 6925 (2003): 787.

Federal Consortium for Advanced Batteries, US Department of Energy. "National Blueprint for Lithium Batteries 2021–2030." https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf.

Feynman, Richard P. "There's Plenty of Room at the Bottom." *Resonance* 16, no. 9 (2011): 890–905.

Fleury, Paul A. "Changes in Federal Academic Research Obligations by Field." Working Paper. Yale School of Engineering, New Haven, CT, 2007.

Fishman, Charles. One Giant Leap: *The Impossible Mission that Flew Us to the Moon*. New York: Simon & Schuster, 2019.

Fong, Glenn R. "ARPA Does Windows: The Defense Underpinning of the PC Revolution." *Business and Politics* 3, no. 3 (2001): 213–37.

Fong, Glenn R. "Breaking New Ground or Breaking the Rules: Strategic Reorientation in U.S. Industrial Policy." *International Security* 25, no. 2 (2000): 152–86.

Fong, Glenn R. "The Potential for Industrial Policy: Lessons from the Very High Speed Integrated Circuit Program." *Journal of Policy Analysis and Management* 5, no. 2 (1986): 264–91.

Fox, Justin. "From 'Economic Man' to Behavioral Economics." *Harvard Business Review* 93, no. 5 (2015): 75–85.

Freeman, Christopher. "Innovation and Long Cycles of Economic Development." *SEMINÁRIO INTERNACIONAL. Universidade Estadual de Campinas, Campinas, Brazil* (1982): 1–13.

Freeman, Christopher. *Technology Policy and Economic Performance: Lessons from Japan*. London: Frances Printer Publishers, 1987.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Freeman, Christopher, John Clark, and Luc Soete. *Unemployment and Technical Innovation: A Study of Long Waves and Economic Development*. London: Frances Pinter, 1982.

Freeman, Richard B. *America Works: Thoughts on an Exceptional U.S. Labor Market*. New York: Russell Sage Foundation, 2007.

Friedman, Benjamin M. *The Moral Consequences of Economic Growth*. New York: Knopf, 2005.

Froomkin, A. Michael. "Reinventing the Government Corporation." *University of Illinois Law Review* (1995).

Frost, Robert. *North of Boston*. New York: Henry Holt, 1915.

Fuchs, Erica R. H. "Cloning DARPA Successfully." *Issues in Science and Technology* 26, no. 1 (2009): 65–70.

Fukuyama, Francis. "The End of History?" *The National Interest* no. 16 (Summer 1989): 3–18.

Furman, Jason, and Wilson Powell. "US Wages Grew at Fastest Pace in Decades in 2021, But Prices Grew Even More." *RealTime Economics* blog post. Peterson Institute for International Economics, January 22, 2022. https://www.piie.com/blogs/realtime-economic-issues-watch/us-wages-grew-fastest-pace-decades-2021-prices-grew-even-more.

Gaddy, Benjamin, Varun Sivaram, and Francis O'Sullivan. "Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation." MIT Energy Initiative working paper. July 2016. https://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf.

Gayle, F., M. Molnar, J. Roth, and Z. Brunner. *Manufacturing USA 2019/2020 Highlights Report*. Advanced Manufacturing Series. Gaithersburg, MD: National Institute of Standards and Technology, 2021. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=931776.

Geddes, Linda. "Taming the Spike: How Jason McLellan Helped Turn the Tide of the Pandemic." *Gavi*, May 16, 2022. https://www.gavi.org/vaccineswork/taming-spike-how-jason-mclellan-helped-turn-tide-pandemic.

Gelles, David. "The Husband-and-Wife Team Behind the Leading Vaccine to Solve Covid-19." *New York Times*, November 10, 2020. https://www.nytimes.com/2020/11/10/business/biontech-covid-vaccine.html.

Gertner, Jon. *The Idea Factory: Bell Labs and the Great Age of American Innovation*. New York: Penguin, 2012.

Gilbert, Lynn. *Grace Murray Hopper: Women of Wisdom*. Lynn Gilbert, Inc., 2012.

Glim, Melissa. "A Record-Breaking Sprint to Create a COVID-19 Vaccine." NIH Intramural Research Program, blog post. July 12, 2021. https://irp.nih.gov/blog/post/2021/07/a-record-breaking-sprint-to-create-a-covid-19-vaccine.

Gold, Elise. "Two-Thirds of Adults Have Less than a Four-Year Degree." *Economic Snapshot*. Economic Policy Institute, June 22, 2018. https://www.epi.org/publication/two-thirds-of-adults-have-less-than-a-four-year-degree-policymakers-should-work-to-make-college-more-attainable-for-them-but-also-strengthen-labor-protections-that-help-all-workers/.

Golden, Frederic, and Michael D. Lemonick. "The Race Is Over." CNN, June 26, 2000. https://www.cnn.com/ALLPOLITICS/time/2000/06/26/race.html.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Goldin, Claudia, and Lawrence F. Katz. "The Future of Inequality—The Other Reason Education Matters So Much. *Milken Institute Review* (Third Quarter 2009): 28–33. https://scholar.harvard.edu/files/goldin/files/the_future_of_inequality.pdf.

Goldin, Claudia, and Lawrence F. Katz. *The Race Between Education and Technology*. Cambridge, MA: Harvard University Press, 2010.

Goldstein, Amy. *Janesville: An American Story*. New York: Simon & Schuster, 2017.

Good, Chris. "The Solyndra Scandal: What It Is and Why It Matters." *The Atlantic*, September 15, 2011. https://www.theatlantic.com/politics/archive/2011/09/the-solyndra-scandal-what-it-is-and-why-it-matters/245186/.

Granstrand, Ove, and Marcus Holgersson. "Innovation Ecosystems: A Conceptual Review and a New Definition." *Technovation* 90 (2020): 102098.

Griffith, Melissa K., and Sophie Goguichvili. "The U.S. Needs a Sustained, Comprehensive, and Cohesive Semiconductor National Security Effort." Strengthening America's Supply Chains blog post. Wilson Center, March 23, 2021. https://www.wilsoncenter.org/blog-post/us-needs-sustained-comprehensive-and-cohesive-semiconductor-national-security-effort.

Gross, Cary P., and Ezekiel J. Emanuel. "The Missing Part of a Pandemic Response." *The Atlantic*, June 5, 2022. https://www.theatlantic.com/ideas/archive/2022/06/nih-covid-vaccine-research-studies/661182/.

Gruber, Jonathan, and Simon Johnson. *Jump-Starting America: How Breakthrough Science Can Revive Economic Growth and the American Dream*. New York: PublicAffairs, 2019.

Gupta, Udayan, ed. *Done Deals: Venture Capitalists Tell Their Stories*. Cambridge, MA: Harvard Business School Press, 2000.

Hamilton, Alexander. *The Papers of Alexander Hamilton, Vol. 11, February 1792–June 1792*. Edited by Harold C. Syrett, 1–15. New York: Columbia University Press, 1966.

Hamilton, Alexander. *The Works of Alexander Hamilton,* edited by Henry Cabot Lodge, 70. New York: G. P. Putnam's Sons, 1904.

Hammond, Samuel. "How Congress Ruined the Endless Frontier Act." Niskanen Center, May 20, 2021. https://www.niskanencenter.org/how-congress-ruined-the-endless-frontier-act/.

Hansen, Kenneth. "The Inflation Reduction Act and DOE Loan Programs." Norton Rose Fulbright, August 17, 2022. https://www.projectfinance.law/publications/2022/august/the-inflation-reduction-act-and-doe-loan-programs/.

Harden, Victoria A. *A Short History of the National Institutes of Health*. Office of History, National Institutes of Health, 1986. https://history.nih.gov/display/history/A+Short+History+of+the+National+Institutes+of+Health.

Harley, Michael. "China Overtakes Japan as the World's Biggest Exporter of Passenger Cars." *Forbes*, May 22, 2023. https://www.forbes.com/sites/michaelharley/2023/05/22/china-overtakes-japan-as-the-worlds-biggest-exporter-of-passenger-cars/.

Harrod, R. F. "An Essay in Dynamic Theory." *The Economic Journal* 49, no. 193 (March 1939): 14–33.

Hart, David M. *Forged Consensus: Science, Technology, and Economic Policy in the United States, 1921–1953*. Princeton, NJ: Princeton University Press, 1998.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Hart, David M. "Herbert Hoover's Last Laugh: The Enduring Significance of the 'Associative State.'" *Journal of Policy History* 10, no. 4 (October 1998): 419–444.

Hart, David M., William B. Bonvillian, and Nathaniel Austin. "Energy Storage for the Grid: Policy Options for Sustaining Innovation." MIT Energy Initiative working paper. 2018. https://energy.mit.edu/wp-content/uploads/2018/04/MITEI-WP-2018-04.pdf.

Hart, Robert. "Reminiscences of James Watt." *Transactions of the Glasgow Archeological Society*, 1859.

Helper, Susan, and Timothy Krueger. *Supply Chains and Equitable Growth*. Washington, DC: Washington Center for Equitable Growth, 2016.

Helper, Susan, Timothy Krueger, and Howard Wial. *Why Does Manufacturing Matter? Which Manufacturing Matters? A Policy Framework*. Washington, DC: Brookings Institution, 2012. https://www.brookings.edu/wp-content/uploads/2016/06/0222_manufacturing_helper_krueger_wial.pdf.

Higgins, Tim. *Power Play: Tesla, Elon Musk, and the Bet of the Century*. New York: Doubleday, 2021.

Hightower, Jim. *There's Nothing in the Middle of the Road But Yellow Stripes and Dead Armadillos*. New York: Harper Perennial, 1998.

Hiltzik, Michael A. *Dealers of Lightning: Xerox PARC and the Dawn of the Computer Age*. New York: HarperCollins, 1999.

Hirsch, Jerry. "Elon Musk's Growing Empire Is Fueled by $4.9 Billion in Government Subsidies." *Los Angeles Times*, May 30, 2015. https://www.latimes.com/business/la-fi-hy-musk-subsidies-20150531-story.html.

Hockfield, Susan. *The Age of Living Machines: How Biology Will Build the Next Technology Revolution*. New York: W. W. Norton and Company, 2019.

Hockfield, Susan, Andrew Liveris, Advanced Manufacturing Partnership Working Group, and Advanced Manufacturing Partnership Steering Committee. "Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing." 2012. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_27_2012.pdf.

Hoddeson, Lillian, and Vicki Daitch. *True Genius—The Life and Science of John Bardeen*. Washington, DC: Joseph Henry Press, 2002.

Hof, Robert D. "Lessons from Sematech." *MIT Technology Review*, July 25, 2011. https://www.technologyreview.com/2011/07/25/192832/lessons-from-sematech/.

Holland, John H. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Cambridge, MA: MIT Press, 1992.

Holland, John H. *Complexity: A Very Short Introduction*. Oxford: Oxford University Press, 2014.

Holland, John H. *Emergence: From Chaos to Order*. New York: Basic Books, 1998.

Holland, John H. *Hidden Order: How Adaptation Builds Complexity*. New York: Basic Books, 1995.

Holland, John H. *Signals and Boundaries: Building Blocks for Complex Adaptive Systems*. Cambridge, MA: MIT Press, 2012.

Holtzman, Yair. "The Research and Development Tax Credit." *CPA Journal*, October 2017. https://www.cpajournal.com/2017/10/30/u-s-research-development-tax-credit/.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Holzer, Harry. "Workforce Development as an Antipoverty Strategy: What Do We Know, What Should We Do?" IZA Discussion Paper No. 3776. Bonn, Germany: Institute for the Study of Labor, October 2008. http:/ftp.iza.org/dp3776.pdf.

Hughes, Kent H. *Building the Next American Century: The Past and Future of American Economic Competitiveness*. Washington, DC: Woodrow Wilson Center Press, 2005.

Hughes, Sally Smith. *Genentech: The Beginnings of Biotech*. Chicago: University of Chicago Press, 2011.

Hunt, Will. "Sustaining U.S. Competitiveness in Semiconductor Manufacturing: Priorities for CHIPS Act Incentives." *Center for Security and Emerging Technology*, January 2022. https://cset.georgetown.edu/publication/sustaining-u-s-competitiveness-in-semiconductor-manufacturing/.

Infectious Disease Society of America (ISDA). "Bad Bugs, No Drugs: As Antibiotic Discovery Stagnates . . . a Public Health Crisis Brews." July 2004. https://www.idsociety.org/globalassets/idsa/policy--advocacy/current_topics_and_issues/antimicrobial_resistance/10x20/statements/070104-as-antibiotic-discovery-stagnates-a-public-health-crisis-brews.pdf.

Infectious Disease Society of America (ISDA). "IDSA Guidelines on the Treatment and Management of Patients with COVID-19." Updated January 20, 2023. https://www.idsociety.org/practice-guideline/covid-19-guideline-treatment-and-management/.

Institute of Medicine. *Financing Vaccines in the 21st Century: Assuring Access and Availability*. Washington, DC: National Academies Press, 2003.

International Energy Agency. *Clean Energy Innovation*. Paris: International Energy Agency, 2020.

International Energy Agency. *Energy Technology Perspectives 2008: Scenarios and Strategies to 2050*. Paris: International Energy Agency, 2008. https://iea.blob.core.windows.net/assets/0e190efb-daec-4116-9ff7-ea097f649a77/etp2008.pdf.

International Energy Agency. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris: International Energy Agency, October 2021. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

International Energy Agency. "Tracking Clean Energy Progress 2017." https://www.iea.org/reports/tracking-clean-energy-progress-2017.

International Renewable Energy Agency. *World Energy Transitions Outlook 2022: 1.5° C Pathway*. Abu Dhabi: International Renewable Energy Agency, 2022. https://irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022.

Isaacson, Walter. *Elon Musk*. New York: Simon and Shuster, 2023.

Jenkins, Jesse D., Erin N. Mayfield, Jamil Farbes, et al. *Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022*. Princeton, NJ: REPEAT Project, 2022. https://repeatproject.org/docs/REPEAT_IRA_Prelminary_Report_2022-08-04.pdf.

Jie, Yang, Stephanie Yang, and Asa Fitch. "The World Relies on One Chip Maker in Taiwan, Leaving Everyone Vulnerable." *Wall Street Journal*, June 19, 2021. https://www.wsj.com/articles/the-world-relies-on-one-chip-maker-in-taiwan-leaving-everyone-vulnerable-11624075400.

Jing, Yu. "China's Tech Pivot: From Consumer Internet to Hard Tech." *CGTN*, September 24, 2021. https://news.cgtn.com/news/2021-09-23/How-China-reshaped-its-tech-industry—13MX5n0YmDS/index.html.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Johnson, Carolyn Y. "A One-Way Ticket. A Cash-Stuffed Teddy Bear. A Dream Decades in the Making." *Washington Post*, October 1, 2021. https://www.washingtonpost.com/health/2021/10/01/katalin-kariko-covid-vaccines/.

Johnson, Carolyn Y. "A Scientific Hunch. Then Silence. Until the World Needed a Lifesaving Vaccine." *Washington Post*, October 1, 2021. https://www.washingtonpost.com/science/2021/10/01/drew-weissman-mrna-vaccine/.

Johnson, Carolyn Y. "Serendipity and Foresight Prepared the World to Fight the Coronavirus." *Washington Post*, October 1, 2021. https://www.washingtonpost.com/health/2021/10/01/barney-graham-covid-vaccines/.

Johnson, Chalmers. *MITI and the Japanese Miracle: The Growth of Industrial Policy, 1925–1975*. Menlo Park, CA: Stanford University Press, 1982.

Johnson, Katherine. *Reaching for the Moon: The Autobiography of NASA Mathematician Katherine Johnson*. New York: Simon & Schuster, 2019.

Jones, Charles I. "Paul Romer: Ideas, Non-Rivalry, and Endogenous Growth." *Scandinavian Journal of Economics* 121, no. 3 (2019): 859–83.

Jones, Jeffrey M. "Middle-Class Identification Steady in U.S." *Gallup*, May 19, 2022. https://news.gallup.com/poll/392708/middle-class-identification-steady.aspx.

Jorgenson, Dale W. "U.S. Economic Growth in the Information Age." *Issues in Science and Technology* 18, no. 1 (Fall 2001). https://issues.org/jorgenson/.

Kaiser, Jocelyn. "NIH Open Precision Medicine Study to Nation." *Science* 349, no. 6255 (2015): 1433.

Kane, Matt. "Tesla Production Sites by Model Assignment, Capacity." *Inside EVs*, July 21, 2022. https://insideevs.com/news/599706/tesla-production-sites-model-assignment-july2022/.

Kearney, Melissa S., Brad Hershbein, and Elisa Jácome. *Profiles of Change: Employment, Earnings, and Occupations from 1990–2013*. Washington DC: The Hamilton Project at the Brookings Institution, 2015.

Kennedy, Brian, Richard Fry, and Cary Funk. "6 Facts About America's STEM Workforce and Those Training for It." Pew Research Center, April 14, 2021. https://www.pewresearch.org/fact-tank/2021/04/14/6-facts-about-americas-stem-workforce-and-those-training-for-it/.

Keynes, John Maynard. *The General Theory of Employment, Interest and Money*. London: Palgrave Macmillan, 1936.

Kim, W. Chan, and Renée Mauborgne. "Value Innovation." *Harvard Business Review*, July–August, 2004. https://hbr.org/2004/07/value-innovation-the-strategic-logic-of-high-growth.

Krugman, Paul. *The Self-Organizing Economy*. Cambridge, MA: Blackwell, 1996.

Kurani, Nisha, Jared Ortaliza, Emma Wager, Lucas Fox, and Krutika Amin. "How Has U.S. Spending on Healthcare Changed over Time?" *Peterson KFF Health System Tracker*, February 25, 2022. https://www.healthsystemtracker.org/chart-collection/u-s-spending-healthcare-changed-time/#Local%20and%20federal%20expenditures%20on%20public%20health,%20US%20$Millions,%201970-2020.

Lander, Eric S., L. M. Linton, B. Birren, et al. "Initial Sequencing and Analysis of the Human Genome." *Nature* 409, no. 6822 (2001): 860–921.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Lapedus, Mark. "China Accelerates Foundry, Power Semi Efforts." Blog post. *Semiconductor Engineering*, Nov 22, 2021. https://semiengineering.com/china-accelerates-foundry-power-semi-efforts/.

Lapedus, Mark. "A Crisis in DOD's Trusted Foundry Program." Blog post. *Semiconductor Engineering*, October 22, 2018. https://semiengineering.com/a-crisis-in-dods-trusted-foundry-program/.

Lambert, Fred. "Tesla Opening Supercharger Network Will Enable Access to New $7.5 Billion EV Funding in US." *Electrek*, August 3, 2021. https://electrek.co/2021/08/03/tesla-opening-supercharger-network-access-7-billion-ev-funding-us/.

Lazonick, William. "There Went the Sun: Renewable Energy Needs Patient Capital." *HuffPost*, September 23, 2011. https://www.huffpost.com/entry/there-went-the-sun-renewa_b_978572.

Leiner, Barry M., Vinton G. Cerf, David D. Clark, et al. "A Brief History of the Internet." *ACM SIGCOMM Computer Communication Review* 39, no. 5 (2009): 22–31.

Lewis, Paul. "Innovation, Technician Skills, and Vocational Education and Training: Connecting Innovation Systems and Vocational Education and Training." *Journal of Vocational Education and Training* (2023): 1–28.

Liao, Rita. "China Roundup: Keep Down Internet Upstarts, Cultivate Hard Tech." *TechCrunch*, July 31, 2021. https://techcrunch.com/2021/07/31/china-roundup-keep-down-internet-upstarts-cultivate-hard-tech/.

Licklider, Joseph C. R. "Man-Computer Symbiosis." *IRE Transactions on Human Factors in Electronics* HFE-1 (1960): 4–11. http://groups.csail.mit.edu/medg/people/psz/Licklider.html.

Licklider, Joseph C. R. "Memorandum for the Members and Affiliates of the Intergalactic Computer Network." Advanced Research Projects Agency (ARPA), April 23, 1963. https://www.kurzweilai.net/memorandum-for-members-and-affiliates-of-the-intergalactic-computer-network.

Licklider, Joseph C. R., and Weldon E. Clark. *Online Man-Computer Communication*. Cambridge, MA: Bolt Beranek and Newman, August 1962. https://dl.acm.org/doi/pdf/10.1145/1460833.1460847.

Licklider, Joseph C. R., and Robert W. Taylor. "The Computer as a Communication Device." *Science and Technology* 78, no. 2 (1968). https://internetat50.com/references/Licklider_Taylor_The-Computer-As-A-Communications-Device.pdf.

Link, Albert N. "Vannevar Bush: A Public Sector Entrepreneur." *Foundations and Trends® in Entrepreneurship* 18, no. 1 (2022), 1–74.

Lopez, German. "How Congress Wrecked Its Own Science Bill, Explained in 600 Words." *Vox*, June 4, 2021. https://www.vox.com/2021/6/4/22518923/endless-frontier-act-innovation-competition-act-china-congress.

Lott, Melissa C. "Solyndra—Illuminating Energy Funding Flaws." *Scientific American* (2011). https://blogs.scientificamerican.com/plugged-in/solyndra-illuminating-energy-funding-flaws/.

Maher, Emily. "Manufacturing Our Way Back to Full Stock." National Conference of State Legislatures, July 2022. https://www.ncsl.org/state-legislatures-news/details/manufacturing-our-way-back-to-full-stock.

Mahoney, Thomas C., and Susan Helper. "Ensuring American Manufacturing Leadership through Next-Generation Supply Chains." *MForesight*, June 2017. http://mforesight.org/projects-events/supply-chains/.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Majeed, Zaini. "NASA 2008 Contract Saved SpaceX from Fourth Straight Failure, Admits Elon Musk." *Republic World*, August 5, 2021. https://www.republicworld.com/technology-news/science/nasa-2008-contract-saved-spacex-from-fourth-straight-failure-admits-elon-musk.html.

Mandavilli, Apoorva. "New Infectious Threats Are Coming. The U.S. Probably Won't Contain Them." *New York Times*, September 29, 2022. https://www.nytimes.com/2022/09/29/health/pandemic-preparedness-covid-monkeypox.html.

Mansfield, Iain, and Geoffrey Owen, eds. *Visions of ARPA*. London: Policy Exchange, 2021.

Mazzucato, Mariana. *The Entrepreneurial State: Debunking Public Vs. Private Sector Myths*. London: Anthem Press 2015.

Mazzucato, Mariana. *Mission Economy: A Moonshot Guide to Changing Capitalism*. New York: Harper Business, 2021.

Mazzucato, Mariana. "Mission-Oriented Innovation Policies: Challenges and Opportunities." *Industrial and Corporate Change* 27, no. 5 (2018): 803–15.

Mazzucato, Mariana, Rainer Kattel, and Josh Ryan-Collins. "Challenge-Driven Innovation Policy: Towards a New Policy Toolkit." *Journal of Industry, Competition and Trade* 20 (2020): 421–37.

McCartney, Scott. *Eniac: The Triumphs and Tragedies of the World's First Computer*. New York: Berkley Books, 2001.

McGregor, Grady. "China's Tech Crackdown Is Forcing the Venture Capitalist Behind Sequoia China's $9 Billion Fund to Deploy a New Investment Strategy." *Yahoo*, July 21, 2022. https://www.yahoo.com/video/china-tech-crackdown-forcing-venture-083441500.html.

Meckstroth, Daniel J. "The Manufacturing Value Chain Is Bigger Than You Think." MAPI Foundation, February 16, 2016. http://industrialpolicy.us/resources/AmericanManufacturing/TheManufacturingValueChain.pdf.

Melfi, Theodore, dir. *Hidden Figures*. 20th Century Fox, 2016. 2 hrs. 27 mins.

Menon, Adwaita Govind, and Brajaraj Mohanty. "Towards a Theory of 'Dynamic Capability' for Firms." *6th AIMS International Conference on Management* 28 (2008).

Miller, Chip. *Chip War: The Fight for the World's Most Critical Technology*. New York: Simon & Schuster, 2022.

Miller, Joe. *The Vaccine: Inside the Race to Conquer the COVID-19 Pandemic*. New York: St. Martin's Press, 2022.

Mindell, David A. *Digital Apollo: Human and Machine in Spaceflight*. Cambridge, MA: MIT Press, 2008.

Mishel, Lawrence. "Yes, Manufacturing Still Provides a Pay Advantage." *Economic Policy Institute*, March 12, 2018. https://www.epi.org/publication/manufacturing-still-provides-a-pay-advantage-but-outsourcing-is-eroding-it/.

Mislinski, Jill. "Household Incomes: The Decline of the 'Middle Class' 2020 Update." *Advisor Perspectives*, October 29, 2021. https://www.advisorperspectives.com/dshort/updates/2021/10/29/household-incomes-the-decline-of-the-middle-class-2020-update.

MIT Energy Initiative. "The Future of Solar Energy: An Interdisciplinary MIT Study." May 2015. https://energy.mit.edu/wp-content/uploads/2015/05/MITEI-The-Future-of-Solar-Energy.pdf.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

MIT Energy Initiative. "The Future of Energy Storage: An Interdisciplinary MIT Study." June 2022. https://energy.mit.edu/wp-content/uploads/2022/05/The-Future-of-Energy-Storage.pdf.

MIT News Office. "The Engine Announces Second Round of Funding to Support 'Tough Tech' Companies." October 27, 2020. https://news.mit.edu/2020/engine-second-fund-tough-tech-1027.

MIT News Office. "The Engine Expands, Responding to Rapid Growth of 'Tough Tech.'" August 27, 2019. https://news.mit.edu/2019/the-engine-tough-tech-expands-0827.

Mitropoulos, Arielle. "The 35-Year-Old Scientist Who Led Moderna's Efforts to Create a COVID-19 Vaccine." ABC News, December 14, 2020. https://abcnews.go.com/Health/35-year-scientist-led-modernas-efforts-create-covid/story?id=74701220.

Modern Distribution Management (MDM) Staff. "MAPI Forecast: Full Recovery in Sight." *MAPI Foundation*, Domestic Outlook Forecast, Full Recovery in Sight, March 22, 2018. https://www.mdm.com/news/strategy-research/research/mapi-forecast-full-recovery-in-sight/.

Molloy, Raven, Christopher L. Smith, and Abigail K. Wozniak. *Declining Migration with the U.S.: The Role of the Labor Market*. No. 220065. National Bureau of Economic Research, Cambridge, MA.

Molnar, Michael. "Advanced Manufacturing Strategy." Presentation to the National Materials and Manufacturing Board, National Academies of Sciences, July 18, 2023.

Morgan, Daniel J., Lucia L. Lomotan, Kathleen Agnes, Linda McGrail, and Mary-Claire Roghmann. "Characteristics of Healthcare-Associated Infections Contributing to Unexpected In-Hospital Deaths." *Infection Control & Hospital Epidemiology* 31, no. 8 (2010): 864–66.

Morris, Charles R. *The Dawn of Innovation: The First American Industrial Revolution*. New York: PublicAffairs, 2012.

Morris, Edmund. *Edison*. New York: Random House, 2019.

Morrow, Daniel S., and Dr. J. Craig Venter. *Oral History*. Video interview transcript. ComputerWorld Honors Program, 2003.

Motoyama, Yasuyuki. "What Was New About the Cluster Theory? What Could It Answer and What Could It Not Answer?" *Economic Development Quarterly* 22, no. 4 (2008): 353–63.

Mulunovich, Steven, and John M. A. Roy. "The Next Small Thing: An Introduction to Nanotechnology." *Merrill Lynch Report*, September 4, 2001. https://www.slideshare.net/tseitlin/intro-to-nanotechnology-merrill-lynch.

Nager, Adams B. "Trade Vs. Productivity: What Caused U.S. Manufacturing's Decline and How to Revive It." *Information Technology and Innovation Foundation*, February 2017. https://www2.itif.org/2017-trade-vs-productivity.pdf.

Nager, Adams B., and Robert D. Atkinson. "The Myth of America's Manufacturing Renaissance: The Real State of U.S. Manufacturing." *Information Technology and Innovation Foundation*, January 2015. https://www2.itif.org/2015-myth-american-manufacturing-renaissance.pdf.

Nahm, Jonas, and Edward S. Steinfeld. "Scale-up Nation: China's Specialization in Innovative Manufacturing." *World Development* 54 (2014): 288–300.

National Academies of Sciences, Engineering, and Medicine. *An Assessment of ARPA-E*. Washington, DC: National Academies Press, 2017.

National Academies of Sciences, Engineering, and Medicine. *Call to Action for Science Education: Building Opportunity for the Future*. Washington, DC: National Academies Press, 2021.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

National Academies of Sciences, Engineering, and Medicine. *Strategic Long-Term Participation by DOD in Its Manufacturing USA Institutes*. Washington, DC: National Academies Press, 2019.

National Association of Manufacturers. "2019 United States Manufacturing Facts." https://www.nam.org/state-manufacturing-data/2019-united-states-manufacturing-facts/.

National Center for Education, National Assessment of Education Progress (NAEP). "NAEP Report Card: 2019 NAEP Mathematics Assessment." https://www.nationsreportcard.gov/highlights/mathematics/2019/g12/.

National Human Genome Institute, National Institutes of Health (NIH). "20 Years Later, Genomicists Remember White House Event Announcing Draft Human Genome Sequence." July 2, 2020. https://www.genome.gov/about-nhgri/Director/genomics-landscape/July-2-2020-twenty-years-later-genomicists-remember-announcement-of-draft-human-genome-sequence.

National Innovation Initiative, 21st Century Innovation Working Group. "Valuing Long-Term Innovation Strategies." October 2004. https://static1.squarespace.com/static/55e10e30e4b09472b9d0e7da/t/56612e78e4b0af254261d874/1449209464293/Valuing_Long_Term_Innovation_Strategies_1.33.pdf.

National Institute of Standards and Technology (NIST), US Department of Commerce. "30 Years of Advanced Manufacturing." *Infographic*, December 10, 2018. https://www.nist.gov/Mep/Manufacturing-Infographics/30-Years-Advancing-Us-Manufacturing-Mep-National-Network.

National Institute of Standards and Technology (NIST), U.S. Department of Commerce. "CHIPS for America Outlines Vision for the National Semiconductor Technology Center." April 25, 2023. https://www.nist.gov/news-events/news/2023/04/chips-america-outlines-vision-national-semiconductor-technology-center.

National Institute of Standards and Technology (NIST), US Department of Commerce. "Manufacturing USA Highlights Report." November 2021. https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.600-9.pdf.

National Institutes of Health (NIH). "About the NIH Common Fund." https://commonfund.nih.gov/about.

National Institutes of Health (NIH). "Advanced Research Projects Agency for Health (ARPA-H)." https://www.nih.gov/arpa-h.

National Institutes of Health (NIH). "The Brain Initiative." https://braininitiative.nih.gov.

National Institutes of Health (NIH). "NIH Establishes National Center for Advancing Translational Science." Press Release, December 23, 2011. https://www.nih.gov/news-events/news-releases/nih-establishes-national-center-advancing-translational-sciences.

National Institute of Standards and Technology (NIST), CHIPS for America, CHIPS R&D Office. "The Vision for the National Advanced Packaging Manufacturing Program." November 20, 2023. https://www.nist.gov/system/files/documents/2023/11/19/NAPMP-Vision-Paper-20231120.pdf.

National Network for Critical Technology Assessment. "Securing America's Future, A Framework for Critical Technology Assessment." November 2023. https://nncta.org/_files/documents/nncta-final-report.pdf.

National Research Council. *The Advanced Technology Program: Challenges and Opportunities*. Washington, DC: National Academies Press, 1999.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

National Research Council. *An Assessment of the SBIR Program*. Washington, DC: National Academies Press, 2008.

National Research Council. *Continuing Innovation in Information Technology*. Washington, DC: National Academies Press, 2012.

National Research Council. *Enhancing the Vitality of the National Institutes of Health: Organizational Change to Meet New Challenges*. Washington, DC: National Academies Press, 2003.

National Research Council. *Funding a Revolution: Government Support for Computing Research*. Washington, DC: National Academies Press, 1999.

National Research Council. *21st Century Manufacturing: The Role of the Manufacturing Extension Partnership Program*. Washington, DC: National Academies Press, 2013.

National Science Foundation (NSF). "Convergence Accelerator." https://beta.nsf.gov/funding/initiatives/convergence-accelerator.

National Science Foundation (NSF). "Growing Convergence Research at NSF." https://www.nsf.gov/od/oia/growing-convergence-research/index.jsp.

National Science Foundation (NSF). "Learn About Convergence Research." n.d. https://new.nsf.gov/funding/learn/research-types/learn-about-convergence-research.

National Science Foundation (NSF). "Science & Engineering Indicators 2022." Table S3-24, Plans of Foreign Recipients of U.S. S&E Doctorates to Stay in the United States, by Field of Doctorate and Place of Citizenship, 2006–2017. https://ncses.nsf.gov/pubs/nsb20198/data#supplemental-tables.

National Science Foundation (NSF). "The State of U.S. Science and Engineering 2022: U.S. and Global Research and Development." https://ncses.nsf.gov/pubs/nsb20221/u-s-and-global-research-and-development.

National Science Foundation. "The State of U.S. Science and Engineering 2022: U.S. and Global STEM Education and Labor Force." January 2022. https://ncses.nsf.gov/pubs/nsb20221/u-s-and-global-stem-education-and-labor-force.

National Science Foundation (NSF). "Women, Minorities, and Persons with Disabilities in Science and Engineering—Field of Degree: Women." Undated. https://www.nsf.gov/statistics/2017/nsf17310/digest/fod-women/engineering.cfm.

National Venture Capital Association. "Six Charts That Show 2021's Record Year for US Venture Capital." https://pitchbook.com/news/articles/2021-record-year-us-venture-capital-six-charts.

Naughton, Barry. *The Rise of China's Industrial Policy, 1978 to 2020*. Universidad Nacional Autónoma de México, Facultad de Economía, Mexico City, 2021.

Nazemi, Katherine W. "From Startup to Scale-up: How Connecting Startups with Local Manufacturers Can Help Move New Technologies from Prototype to Production." MIT Washington Office, July 2016.

Neal, Homer A., Tobin L. Smith, and Jennifer B. McCormick. *Beyond Sputnik: National Science Policy in the 21st Century*. Ann Arbor: University of Michigan Press, 2008.

Nelson, Richard. "Building Effective Innovation Systems Versus Dealing with Market Failures as Ways of Thinking About Technology Policy." Working Paper No. 548, Manchester Business School, Manchester, UK, 2008. https://www.econstor.eu/handle/10419/50711.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Nelson, Richard R. *National Innovation Systems: A Comparative Analysis*. New York: Oxford University Press, 1993.

Nemet, Gregory F., and Daniel M. Kammen. "U.S. Energy Research and Development: Declining Investment, Increasing Need, and the Feasibility of Expansion." *Energy Policy* 35, no. 1 (2007): 746–55.

Neufeld, Jeremy. "STEM Immigration Is Critical to American National Security." *Institute for Progress*, March 30, 2022. https://progress.institute/stem-immigration-is-critical-to-american-national-security/.

New Jersey Community Development Corporation (NJCDC). "What We Do: History of Paterson." 2023. https://www.njcdc.org/what-we-do/page.php?Revitalizing-Paterson-Great-Falls-Promise-Neighborhood-History-of-Paterson-24.

Nicholson, Jessica R. *What Is Made in America?* ESA Issue Brief 01-17. Washington, DC: US Department of Commerce, March 28, 2017. https://www.commerce.gov/sites/default/files/migrated/reports/2015-what-is-made-in-america_0.pdf.

Organisation for Economic Cooperation and Development (OECD). "Data: Current Account Balance." https://data.oecd.org/trade/current-account-balance.htm#indicator-chart.

Organisation for Economic Cooperation and Development (OECD). "Measuring Distortions in International Markets: The Semiconductor Value Chain." December 12, 2019. https://www.oecd-ilibrary.org/trade/measuring-distortions-in-international-markets_8fe4491d-en.

Organisation for Economic Cooperation and Development (OECD). *Oslo Manual 2018: Guidelines for Collecting and Interpreting Innovation Data*. Paris: OECD Publishing, 2018.

Organisation for Economic Cooperation and Development (OECD). "Trade: Key Tables from OECD." https://www.oecd-ilibrary.org/trade/goods-trade-balance-2012-1_tbal-gds-table-2012-1-en.

Ortiz, Catherine. "Microelectronics in Defense Systems." Presentation at the NDIA Systems Engineering Meeting, December 7, 2016. DMEA Trusted Foundry Program. https://www.ndia.org/-/media/sites/ndia/meetings-and-events/divisions/systems-engineering/past-events/division-meetings/2016-december/ndia-se-tfp-outreach-201612072.ashx.

Pacala, Stephen, and Robert Socolow. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science* 305, no. 5686 (2004): 968–72.

Page, John, and Finn Tarp. *The Practice of Industrial Policy: Government—Business Coordination in Africa and East Asia*. Oxford: Oxford University Press, 2017.

Pain, Stephanie. "Power Through the Ages." *Nature*, November 29, 2017. https://www.nature.com/articles/d41586-017-07506-z.

Perez, Carlota. *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*. Cheltenham, UK: Edward Elgar Publishing, 2003.

Pisano, Gary P., and Willy C. Shih. *Producing Prosperity: Why American Needs a Manufacturing Renaissance*. Cambridge, MA: Harvard Business School Press, 2012.

Pisano, Gary, and Willy C. Shih. "Restoring American Competitiveness." *Harvard Business Review* 87, no. 7/8 (2009): 114–25. https://hbr.org/2009/07/restoring-american-competitiveness/ar/1.

PitchBook Data and National Venture Capital Association (NCVA). "Venture Monitor Pitchbook 2021." Updated January 13. 2022. https://pitchbook.com/news/reports/q4-2021-pitchbook-nvca-venture-monitor.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Podesta, John, Todd Stern, and Kit Batten. *Capturing the Energy Opportunity: Creating a Low-Carbon Economy*. Washington, DC: Center for American Progress, 2007.

Polanyi, Michael. *The Tacit Dimension*. Chicago: University of Chicago Press, 1966.

Porter, Michael E. "Clusters and the New Economics of Competition." *Harvard Business Review* 76, no. 6 (1998).

President's Council of Advisors on Science and Technology. "Capturing Domestic Competitive Advantage in Advanced Manufacturing: AMP Steering Committee Report." July 2012. https://s3.amazonaws.com/sitesusa/wp-content/uploads/sites/802/2017/06/pcast_amp_steering_committee_report_final_july_27_2012.pdf.

Price, David A. *Geniuses at War: Bletchley Park, Colossus, and the Dawn of the Digital Age*. New York: Knopf, 2021.

Price, Laurie J. "A Medical Anthropologist's Ruminations on NIH Funding." *Medical Anthropology Quarterly* 6, no. 2 (1992): 128–46.

Promislo, Mark. "The NIH's Slow Response to the AIDS Epidemic and the Dismissal of Pasteur's Contributions: Learning from History." *International Journal of Health Planning Management* 34, no.1 (2019): 8–14.

Pundziene, Asta, and David J. Teece. "New Applications of Dynamic Capability Research." *Baltic Journal of Management* 11, no. 3 (2016): 234–37.

Reeves, Richard V., Christopher Pullam, and Ashley Schobert. "Are Wages Rising, Falling, or Stagnating?" Up Front blog post. Brookings Institution, September 10, 2019. https://www.brookings.edu/blog/up-front/2019/09/10/are-wages-rising-falling-or-stagnating/.

Reif, L. Rafael. "A Better Way to Deliver Innovation to the World." *Washington Post*, May 22, 2015. https://www.washingtonpost.com/opinions/a-better-way-to-deliver-innovation-to-the-world/2015/05/22/35023680-fe28-11e4-8b6c-0dcce21e223d_story.html.

Reischauer, Haru Matsukata. *Samurai and Silk: A Japanese and American Heritage*. Cambridge, MA: Harvard University Press, 1986.

Reynolds, Elisabeth, Dan Traficonte, and Anna Waldman-Brown. "Strengthening Manufacturing Innovation Ecosystems Before, During, and After COVID: Lessons from Massachusetts." MIT Work of the Future Working Paper 11-2021. Massachusetts Institute of Technology, Cambridge, MA, January 22, 2021.

Rezvani, Arezou. "You Can Get a $7,500 Tax Credit to Buy an Electric Car, But It's Really Complicated." National Public Radio, August 22, 2022. https://www.npr.org/2022/08/22/1118052620/tax-credit-electric-cars-vehicles-tesla-gm-inflation-reduction-act-climate.

Rich, Ben R., and Leo Janos. *Skunk Works: A Personal Memoir of My Years at Lockheed*. Boston: Little, Brown, and Co., 1994.

Rithmire, Meg. "The Resurgent Role of the State in China's Economy: Experimentation, Domestic Politics, and U.S. Policy." Working paper for the Penn Project on the Future of U.S.-China Relations. Updated Spring 2021. https://cpb-us-w2.wpmucdn.com/web.sas.upenn.edu/dist/b/732/files/2021/04/Meg-Rithmire_The-Resurgent-Role-of-the-State-in-Chinas-Economy_Updated.pdf.

Roberts, Leslie. "Genome Patent Fight Erupts." *Science* 254, no. 5029 (1991): 184–86.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Robertson, Cassandra, and Darrick Hamilton. "Economic Rights as Industrial Policy." *The American Prospect*, October 21, 2020. https://prospect.org/familycare/economic-rights-as-industrial-policy/.

Robyn, Dorothy. "Mission, Money, and Process Makeover: How Federal Procurement Can Catalyze Clean Energy Investment and Innovation." Information Technology and Innovation Foundation, August 15, 2022. https://www2.itif.org/2022-federal-buying-power.pdf.

Rockwell, Jonathan. "The Hidden STEM Economy." Brookings Institution, Washington, DC, June 10, 2013. https://www.brookings.edu/research/the-hidden-stem-economy/.

Roco, Mihail C., William S. Bainbridge, Bruce Tonn, and George Whitesides, eds. *Convergence of Knowledge, Technology and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies*. Cham, Switzerland: Springer, 2013.

Rodrik, Dani. *Straight Talk on Trade: Ideas for a Sane World*. Princeton, NJ: Princeton University Press, 2017.

Roessner, David, Jennifer Bond, Sumiye Okubo, and Mark Planting. "The Economic Impact of Licensed Commercialized Inventions Originating in University Research." *Research Policy* 42, no. 1 (2013): 23–34.

Roland, Alex. "Cloning DARPA." *Issues in Science and Technology Policy* 26, no. 2 (2010): 10–11.

Roland, Alex, and Philip Shiman. *Strategic Computing: DARPA and the Quest for Machine Intelligence, 1983–1993*. Cambridge, MA: MIT Press, 2002.

Romer, Paul M. "The Dismal Kingdom: Do Economists Have Too Much Power?" *Foreign Affairs* 99 (March/April 2020): 150. https://www.foreignaffairs.com/reviews/dismal-kingdom.

Romer, Paul M. "Endogenous Technological Change." *Journal of Political Economy* 98, no. 5, Part 2 (1990): S71–S102.

Romer, Paul M. "Mathiness of the Theory of Economic Growth." *American Economic Review* 105, no. 5 (2015): 89–93.

Romer, Paul M. "Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?" *Innovation Policy and the Economy* 1 (2000): 221–52.

Romer, Paul M. "The Trouble with Macroeconomics." September 14, 2016. http://ccl.yale.edu/sites/default/files/files/The Trouble with Macroeconomics.pdf.

Romer, Paul. "What Went Wrong." *Paul Romer* (blog). February 10, 2020. https://paulromer.net/what-went-wrong/.

Roosevelt, Franklin D. "Letter on the Office of Scientific Research and Development." *Science*, December 15, 1944. https://www.science.org/doi/pdf/10.1126/science.100.2607.542.a.

Root, Al. "Tesla and BYD are Beating their EV Rivals in China, Data Show." *Barron's*, March 3, 2023. https://www.barrons.com/articles/tesla-byd-china-ev-market-share-232ccf56#:~:text=Tesla's%20share%20of%20the%20total,hybrids%20and%20battery%20electric%20vehicles.

Rosen, William. *The Most Powerful Idea in the World*. New York: Random House, 2010.

Rotman, David. "Nicholas Stern." *MIT Technology Review,* June 21, 2011. https://www.technologyreview.com/2011/06/21/193615/nicholas-stern/.

Ruegg, Rosalie, Irwin Feller, and Philip J. Bond. "A Toolkit for Evaluating Public R&D Investments: Models, Methods, and Findings from ATP's First Decade." National Institute of Standards and

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Technology. NIST GCR 03-857. 2003. https://nvlpubs.nist.gov/nistpubs/gcr/2003/NIST.GCR.03-857.pdf.

Ruttan, Vernon W. "Induced Innovation and Agricultural Development." *Food Policy* 2, no. 3 (1977): 196–216.

Ruttan, Vernon W. *Is War Necessary for Economic Growth? Military Procurement and Technology Development*. New York: Oxford University Press, 2006.

Ruttan, Vernon W. *Technology Growth and Development: An Induced Innovation Perspective*. New York: Oxford University Press, 2001.

Rycroft, Robert W., and Don E. Kash. "Innovation Policy for Complex Technologies." *Issues in Science and Technology* 16, no. 1 (1999): 73–79.

Sagers, John H. *Origins of Japanese Wealth and Power: Reconciling Confucianism and Capitalism, 1830–1885*. New York: Palgrave Macmillan, 2006.

Sainsbury, David. *Windows of Opportunity: How Nations Create Wealth*. London: Profile Books, 2020.

Samuelson, Paul A. "Where Ricardo and Mill Rebut and Confirm Arguments of Mainstream Economists Supporting Globalization." *Journal of Economic Perspectives* 18, no. 3 (2004): 135–46.

Sarma, Sanjay E., and William B. Bonvillian. "Fixing an Imperfect Labor Market Information System." *Issues in Science and Technology* 35, no. 1 (2018): 56–61.

Sarma, Sanjay E., and William B. Bonvillian. "The Quest for Quality Jobs." *Issues in Science and Technology* 25, no. 1 (2018): 28–30.

Sarma, Sanjay E., and Luke Yoquinto. *Grasp: The Science of Transforming How We Learn*. New York: Anchor Books, 2021.

Schein, Edgar H., Peter S. DeLisi, Paul J. Kampas, and Michael M. Sonduck. *DEC Is Dead, Long Live DEC*. Oakland, CA: Berrett-Koehler Publishers, 2003.

Schneider, Eric C., Arnav Shah, Pratha Sah, et al. "Impact of U.S. COVID-19 Vaccination Efforts: An Update on Averted Death, Hospitalizations, and Health Care Costs Through March 2022." Commonwealth Fund, April 8, 2022. https://www.commonwealthfund.org/blog/2022/impact-us-covid-19-vaccination-efforts-march-update.

Schultze, Charles L. "Industrial Policy: A Dissent." *Brookings Review* 2, no. 1 (1983): 3–12.

Schumpeter, Joseph. *Capitalism, Socialism, and Democracy*. New York: Harper and Brothers, 1942.

Schwab, Klaus, and Saadia Zahidi. "Global Competitiveness Report: Special Edition 2020." World Economic Forum, Cologny, Switzerland, 2020. https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2020.pdf.

Scott, Robert E. "Manufacturing Job Loss: Trade, Not Productivity, Is the Culprit." Economic Policy Institute, Washington, DC, August 11, 2015. https://www.epi.org/publication/manufacturing-job-loss-trade-not-productivity-is-the-culprit/.

Scott, Robert E., and Zane Mokhiber. "Growing China Trade Deficit Cost 3.7 Million American Jobs Between 2001 and 2018: Jobs Lost in Every U.S. State and Congressional District." Economic Policy Institute, Washington, DC, January 30, 2020. https://www.epi.org/publication/growing-china-trade-deficits-costs-us-jobs/.

Sekar, Kavya. "National Institutes of Health (NIH) Funding: FY1996–FY2023." Congressional Research Service, Washington, DC, March 8, 2023. https://crsreports.congress.gov/product/pdf/R/R43341.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Semiconductor Industry Association. "Semiconductor 2019 Factbook." Washington, DC. https://www.semiconductors.org/wp-content/uploads/2019/05/2019-SIA-Factbook-FINAL.pdf.

Sen, Avery. "Totally Radical: From Transformative Research to Transformative Innovation." *Science and Public Policy* 41, no. 3 (2013): 344–58.

Sen, Avery. "Transformative Innovation." PhD diss., George Washington University, Washington, DC, 2014.

Sennet, Richard. *The Craftsman*. New Haven, CT: Yale University Press, 2008.

Service, Robert F. "'Big Step Forward.' Energy Expert Analyzes the New U.S. Infrastructure Bill." *Science Insider*, August 11, 2021. https://www.science.org/content/article/big-step-forward-energy-expert-analyzes-new-us-infrastructure-bill.

Shapira, Philip, and Jan Youtie. "Next Production Revolution: Institutions for Technology Diffusion." Presentation at the Conference on Smart Industry: Enabling the Next Production Revolution of the OECD and Government Offices of Sweden, Ministry of Enterprise and Innovation, Stockholm, November 18, 2016. https://www.oecd.org/sti/ind/161118_Shapira.pdf.

Shapley, Deborah, and Rustum Roy. *Lost at the Frontier: U.S. Science and Technology Policy Adrift*. Philadelphia: ISI Press, 1985.

Sharp, Phillip A., Charles L. Cooney, Marc A. Kastner, et al. "The Third Revolution: The Convergence of the Life Sciences, Physical Sciences, and Engineering." Massachusetts Institute of Technology, 2011.

Sharp, Phillip A., Susan Hockfield, and Tyler Jacks. *Convergence: The Future of Health*. Cambridge, MA: Massachusetts Institute of Technology, 2016. http://www.convergencerevolution.net.

Sharp, Phillip A., and Robert Langer. "Promoting Convergence in Biomedical Science." *Science* 333, no. 6042: (2011): 527.

Shetterly, Margot Lee. *Hidden Figures: The American Dream and the Untold Story of the Black Women Mathematicians Who Helped Win the Space Race*. New York: William Morrow, 2016.

Shin, Hyun Song. *Global Value Chains Under the Shadow of COVID*. Basel, Switzerland: Bank for International Settlements, February 16, 2023. https://www.bis.org/speeches/230216_shin.pdf.

Shreeve, James. *The Genome War: How Craig Venter Tried to Capture the Code of Life and Save the World*. New York: Alfred A. Knopf, 2004.

Singer, Peter L. *Federally Supported Innovations: 22 Examples of Major Technology Advances that Stem from Federal Research Support*. Washington, DC: International Technology & Innovation Foundation, 2014. https://www2.itif.org/2014-federally-supported-innovations.pdf.

Singer, Peter L., and William B. Bonvillian. "'Innovation Orchards': Helping Tech Start-ups Scale." Information Technology and Innovation Foundation, March 2017. https://www2.itif.org/2017-innovation-orchards.pdf.

Slaoui, Moncef, and Matthew Hepburn. "Developing Safe and Effective Covid Vaccines—Operation Warp Speed's Strategy and Approach." *New England Journal of Medicine* 383, no. 18 (2020): 1701–3.

Smith, Douglas K., and Robert C. Alexander. *Fumbling the Future: How Xerox Invented, Then Ignored, the First Personal Computer*. New York: William Morrow, 1988.

Smith, Mark K. "Michael Polanyi and Tacit Knowledge." In *The Encyclopedia of Pedagogy and Informal Education* 2003. https://infed.org/mobi/michael-polanyi-and-tacit-knowledge/.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Smith, Merritt Roe. "George Washington and the Establishment of the Harpers Ferry Armory." *Virginia Magazine of History and Biography* 81, no. 4 (1973): 415–36.

Smith, Merritt Roe. *Harpers Ferry Armory and the New Technology: The Challenge of Change*. Ithaca, NY: Cornell University Press, 1980.

Society for Establishing Useful Manufactures. "Prospectus of the Society for Establishing Useful Manufactures." August 1791. https://founders.archives.gov/documents/Hamilton/01-09-02-0114.

Solow, Robert M. *Building a Science of Economics for the Real World: Testimony to the Investigations Subcommittee of the House Committee on Science and Technology*, 111th Cong., 2nd Sess. July 20, 2010. https://www.govinfo.gov/content/pkg/CHRG-111hhrg57604/pdf/CHRG-111hhrg57604.pdf.

Solow, Robert M. "Growth Theory and After." Transcript of Nobel Prize Lecture. December 8, 1987. https://www.nobelprize.org/prizes/economic-sciences/1987/solow/lecture/.

Solow, Robert M. *Growth Theory: An Exposition*. New York: Oxford University Press, 2000. Originally published in 1970.

Sonne, Paul. "How a Secretive Pentagon Agency Seeded the Ground for a Rapid Coronavirus Cure." *Washington Post*, July 30, 2020. https://www.washingtonpost.com/national-security/how-a-secretive-pentagon-agency-seeded-the-ground-for-a-rapid-coronavirus-cure/2020/07/30/ad1853c4-c778-11ea-a9d3-74640f25b953_story.html.

Spar, Debora L. *Ruling the Waves: Cycles of Discovery, Chaos, and Wealth from Compass to the Internet*. New York: Harcourt, 2001.

Spence, A. Michael. "The Impact of Globalization on Income and Employment: The Downside of Integrating Markets." *Foreign Affairs* 90, no. 4 (2011): 28–41.

Statista, "China Is the World's Manufacturing Superpower," https://www.statista.com/chart/20858/top-10-countries-by-share-of-global-manufacturing-output/.

Statistia. "Number of Motor Vehicles Registered in the United States from 1990 to 2021." https://www.statista.com/statistics/183505/number-of-vehicles-in-the-united-states-since-1990/.

Statista. "Trade Deficit of Goods Manufactured in the United States from 2000 to 2016." https://www.statista.com/statistics/814589/manufactured-goods-trade-deficit-us/.

Statista. "U.S. National Health Expenditure as Percent of GDP from 1960 to 2021." December 2022. https://www.statista.com/statistics/184968/us-health-expenditure-as-percent-of-gdp-since-1960/.

Stec, Connor. "The Implications of American Wage Stagnation." *USC Economics Review*, March 28, 2021. https://usceconreview.com/2021/03/28/the-implications-of-american-wage-stagnation/.

Stettner, Andrew, Joel S. Yudken, and Michael McCormack. "Why Manufacturing Jobs Are Worth Saving." The Century Foundation, New York, June 13, 2017. https://tcf.org/content/report/manufacturing-jobs-worth-saving/.

Stewart, Luke A., and Robert D. Atkinson. "Restoring America's Lagging Investment in Capital Goods." Report. Information Technology and Innovation Foundation, Washington, DC, 2013.

Stiles, T. J. *The First Tycoon: The Epic Life of Cornelius Vanderbilt*. New York: Knopf, 2009.

St. John, Jeff. "The Rules for Early-Stage Cleantech Venture Capital Investment in 2021." *Greentech Media*, February 1, 2021. https://www.greentechmedia.com/articles/read/lessons-for-early-stage-greentech-venture-investing-for-the-next-decade.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

St. Louis Federal Reserve Bank, "All Employees, Manufacturing," https://fred.stlouisfed.org/series/MANEMP.

Stokes, Donald E. *Pasteur's Quadrant: Basic Science and Technological Innovation*. Washington, DC: Brookings Institution Press, 2011. Originally published in 1997.

Stolper, Wolfgang F., and Paul A. Samuelson. "Protection and Real Wages." *Review of Economic Studies* 9, no. 1 (1941): 58–73.

Strain, Michael R. "Stapling Green Cards to Diplomas: Time to Make This Cliché a Law." *The Atlantic*, June 21, 2012. https://www.theatlantic.com/business/archive/2012/06/stapling-green-cards-to-diplomas-time-to-make-this-cliche-a-law/258803/.

Strub, Doug. "China's Innovation Policy and the Quest for Semiconductor Autonomy—Q&A with Dieter Ernst." *AmCham Shanghai*, May 23, 2019. https://www.amcham-shanghai.org/en/article/semiconductor-dieter-ernst.

Temple, James. "How VCs Can Avoid Another Bloodbath as the Clean-tech Boom 2.0 Begins." *MIT Technology Review*, November 30, 2020. https://www.technologyreview.com/2020/11/30/1012660/venture-capital-clean-tech-boom-biden/.

Thompson, William E., Joseph V. Hickey, and Mica L. Thompson. *Society in Focus: An Introduction to Sociology*. Lanham, MD: Rowman and Littlefield 2018.

Thum-Thysen, Anna, Peter Voigt, Benat Bilbao-Osorio, Christoph Maier, and Diana Ognyanova, "Unlocking Investment in Intangible Assets." European Economy Discussion Paper 047, European Commission. Luxembourg: Publications Office of the European Union, 2017. https://ec.europa.eu/info/sites/default/files/economy-finance/dp047_en.pdf.

Tollefson, Jeff. "The Rise of 'ARPA-everything' and What It Means for Science." *Nature* 595, no. 7868 (2021): 483–84.

Tooze, Adam. *Shutdown: How Covid Shook the World's Economy*. New York: Penguin, 2021.

Torpey, Elka. "Got Skills? Think Manufacturing." US Bureau of Labor Statistics, Career Outlook, June 2014. https://www.bls.gov/careeroutlook/2014/article/manufacturing.htm.

Trewin, Shaun. "The Incredible Story of Genentech and How It All Started with a Beer." *Quality Compounders*, November 12, 2020. https://www.qualitycompounders.com.au/post/the-incredible-story-of-genentech-and-how-it-all-started-with-a-beer.

Triolo, Paul. "The Future of China's Semiconductor Industry." *American Affairs* 5, no. 1 (2021). https://americanaffairsjournal.org/2021/02/the-future-of-chinas-semiconductor-industry/.

Tucker, Todd. "Industrial Policy and Planning: What It Is and How to Do It Better." *Roosevelt Institute*, 2019. https://rooseveltinstitute.org/publications/industrial-policy-and-planning/.

Turner, Frederick Jackson. *The Frontier in American History*. New York: Henry Holt, 1920.

Uchitelle, Louis. *Making It: Why Manufacturing Still Matters*. New York: New Press, 2017.

United Nations Conference on Trade and Development (UNCTAD). "Virtual Institute Teaching Material on Structural Transformation and Industrial Policy." Geneva, Switzerland. 2016. https://unctad.org/system/files/non-official-document/indpolfull_UNCTAD_material.pdf.

United Nations Environment Programme. "Treaties." https://ozone.unep.org/treaties/montreal-protocol.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

United Nations Framework Convention of Climate Change. "The Paris Agreement." https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

US Department of the Air Force, Office of the Chief Scientist, NDAA 2023. "Mandated Independent Review of USD (R&E) Microelectronics Quanltifiable Assurance Effort." August 3, 2023, https://www.af.mil/Portals/1/documents/2023SAF/MQA_Report.pdf.

U.S. Department of Defense (DOD). "The Microelectronics Commons: A National Network of Prototyping Innovation Hubs." Microelectronics Commons. https://microelectronicscommons.org.

US Bureau of Economic Analysis. "U.S. International Trade in Goods and Services (1960–2021)." https://www.bea.gov/data/intl-trade-investment/international-trade-goods-and-services.

US Census Bureau. "Census Bureau Releases New Educational Attainment Data." Press Release No. CB23-TPS.21. February 16, 2023. https://www.census.gov/newsroom/press-releases/2023/educational-attainment-data.html#:~:text=28%25%20had%20high%20school%20as,degree%20as%20their%20highest%20degree.

US Census Bureau. "International Trade in Goods and Services." https://www.census.gov/foreign-trade/Press-Release/current_press_release/index.html.

US Census Bureau. "Trade in Goods with Advanced Technology Products." https://www.census.gov/foreign-trade/balance/c0007.html.

US Department of Defense (DOD), Office of the Secretary, Acquisition and Sustainment Industrial Policy Office. "Fiscal Year 2020 Industrial Capabilities Report to Congress." https://media.defense.gov/2021/Jan/14/2002565311/-1/-1/0/FY20-INDUSTRIAL-CAPABILITIES-REPORT.PDF.

US Department of Defense (DOD), Office of the Secretary, Trusted Access Program Office, Defense Microelectronics Activity. "DMEA Trusted IC Program." n.d. https://www.dmea.osd.mil/TrustedIC.aspx.

US Department of Energy (DOE). "Appliance and Equipment Standards Program." https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program.

US Department of Energy (DOE). "Biden Administration, DOE to Invest $3 Billion to Strengthen U.S. Supply Chain for Advanced Batteries for Vehicles and Energy Storage." Energy.gov, February 11, 2022. https://www.energy.gov/articles/biden-administration-doe-invest-3-billion-strengthen-us-supply-chain-advanced-batteries.

US Department of Energy (DOE). "DOE Announces $209 Million for Electric Vehicles Battery Research." Energy.gov, October 27, 2021. https://www.energy.gov/articles/doe-announces-209-million-electric-vehicles-battery-research.

US Department of Energy (DOE). "Office of Technology Transitions." https://www.energy.gov/technologytransitions/office-technology-transitions.

US Department of Energy (DOE). "Renewable Energy Explained." https://www.eia.gov/energyexplained/renewable-sources/portfolio-standards.php.

US Department of Energy (DOE), Loan Programs Office. "Tesla." n.d. https://www.energy.gov/lpo/tesla.

US Department of Energy (DOE), Office of Science, Office of Biological and Environmental Research. "Human Genome Project Information Archive 1990–2003." https://web.ornl.gov/sci/techresources/Human_Genome/project/whydoe.shtml.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

US Department of Health and Human Services (HHS), Administration for Strategic Preparedness and Response. "Fact Sheet: $5 Billion 'Project NextGen' Initiative to Stay Ahead of COVID-19." May 11, 2023. https://aspr.hhs.gov/newsroom/Pages/ProjectNextGen-May2023.aspx.

US Department of Labor. "Registered Apprenticeship National Results Fiscal Year 2021." https://www.dol.gov/agencies/eta/apprenticeship/about/statistics/2021.

US Department of Transportation, Bureau of Transportation Statistics. "Average Age of Automobiles and Trucks in the United States." https://www.bts.gov/content/average-age-automobiles-and-trucks-operation-united-states (this includes passenger cars and light trucks.

US Department of Transportation, Bureau of Transportation Statistics. "Annual U.S. Motor Vehicle Sales." Table 1-15, 2020. https://www.bts.gov/content/annual-us-motor-vehicle-production-and-factory-wholesale-sales-thousands-units.

US Energy System Facts. "U.S. Energy System Factsheet." https://css.umich.edu/publications/factsheets/energy/us-energy-system-factsheet.

US Environmental Protection Agency (EPA). "Transportation, Air Pollution, and Climate Change." https://www.epa.gov/transportation-air-pollution-and-climate-change.

US Food and Drug Administration (FDA), US Department of Health and Human Services (HHS). *Advancing Regulatory Science at FDA: Focus Areas of Regulatory Science (FARS)*. Silver Spring, MD: Food and Drug Administration (FDA), 2021. https://www.fda.gov/media/145001/download#:~:text=As%20such%2C%20FDA%20identified%20the,and%20the%20One%20Health%20Initiative.

US Food and Drug Administration (FDA), US Department of Health and Human Services (HHS). "Critical Path Reports," 2004–2011. http://wayback.archive-it.org/7993/20180125075636/https:/www.fda.gov/ScienceResearch/SpecialTopics/CriticalPathInitiative/CriticalPathOpportunitiesReports/default.htm.

US Food and Drug Administration (FDA), US Department of Health and Human Services (HHS). "FDA's Critical Path Initiative," January 25, 2016. http://wayback.archive-it.org/7993/20180125035414/https:/www.fda.gov/ScienceResearch/SpecialTopics/CriticalPathInitiative/ucm076689.htm.

US Food and Drug Administration (FDA), US Department of Health and Human Services (HHS). "Innovation/Stagnation: Challenge and Opportunity on the Critical Path to New Medical Products," March 2004. http://wayback.archive-it.org/7993/20180125035500/https://www.fda.gov/downloads/ScienceResearch/SpecialTopics/CriticalPathInitiative/CriticalPathOpportunitiesReports/UCM113411.pdf.

US Government Accountability Office. "The Nation's Fiscal Health: After Pandmic Recovery, Focus Needed on Achieving Long-Term Fiscal Sustainability." March 2021. https://www.gao.gov/assets/gao-21-275sp.pdf.

US Energy Information Administration. "U.S. Energy Facts Explained." https://www.eia.gov/energyexplained/us-energy-facts/.

Usher, Abbott Payson. *A History of Mechanical Inventions*. Rev. ed. Cambridge, MA: Harvard University Press, 1954. Originally published in 1929.

US Small Business Administration. "About the SBIR and STTR Programs." Undated. https://www.sbir.gov/about.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

US Trade Representative. "The People's Republic of China." https://ustr.gov/countries-regions/china-mongolia-taiwan/peoples-republic-china.

Utterback, James M., and William J. Abernathy. "A Dynamic Model of Process and Product Innovation." *Omega* 3, no. 6 (1975): 639–56.

Van Atta, Richard H. "Fifty Years of Innovation and Discovery." In *DARPA, 50 Years of Bridging the Gap*. Edited by C. Oldham, A. E. Lopez, R. Carpenter, I. Kalhikina, and M. J. Tully. Arlington, VA: DARPA, 2008.

Van Atta, Richard H., Alethia Cook, Ivars Gutmanis, et al. *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs. Volume 2, Detailed Assessments*. Alexandria, VA: Institute for Defense Analyses, 2003. https://apps.dtic.mil/sti/pdfs/ADA422835.pdf.

Van Atta, Richard H., Michael J. Lippitz, Jasper C. Lupo, Rob Mahoney, and Jack H. Nunn. *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs. Volume 1, An Overall Assessment*. Alexandria, VA: Institute for Defense Analyses, 2003. https://irp.fas.org/agency/dod/idarma.pdf.

Vance, Ashlee. *Elon Musk: Tesla, SpaceX, and the Quest for a Fantastic Future*. New York: Harper Collins, 2015.

Van Sloun, Sherry. "U.S. Investment in Semiconductor Manufacturing: Building the Talent Pipeline." Council on Foreign Relations, September 18, 2023. https://www.cfr.org/blog/us-investment-semiconductor-manufacturing-building-talent-pipeline#:~:text=Currently%2C%20the%20United%20States%20manufactures,and%20hardware%20education%20to%20stagnate.

Vardi, Nathan. "The Race Is On: Why Pfizer May Be the Best Bet to Deliver a Vaccine by the Fall." *Forbes*, May 20, 2020. https://www.forbes.com/sites/nathanvardi/2020/05/20/the-man-betting-1-billion-that-pfizer-can-deliver-a-vaccine-by-this-fall.

Varmus, Harold. *The Art and Politics of Science*. New York: W. W. Norton & Company, 2010.

Venter, J. Craig. *A Life Decoded: My Genome, My Life*. New York: Viking, 2007.

Venter, J. Craig, Mark D. Adams, Eugene W. Myers, et al. "The Sequence of the Human Genome." *Science* 291, no. 5507 (2001): 1304–51.

Venter, J. Craig, Mark D. Adams, Granger G. Sutton, Anthony R. Kerlavage, Hamilton O. Smith, and Michael Hunkapiller. "Shotgun Sequencing of the Human Genome." *Science* 280, no. 5369. (1998): 1540–42.

Vernon, Raymond. "International Investment and International Trade in the Product Cycle." *The Quarterly Journal of Economics* 80, no. 2 (1966): 190–207.

Vidyasagar, Dharmapuri. "Global Notes: The 10/90 Gap Disparities in Global Health Research. *Journal of Perinatology* 26, no. 1 (2006): 55–56.

Vonortas, Nicholas S. "Innovation and Public Procurement in the United States." In *Public Procurement for Innovation,* edited by Charles Edquist, Nicholas S. Vonortas, and Mikel Zabala-Iturriagagoitia. Cheltenham, UK: Edward Elgar Publishing, 2015.

Wade, Nicholas. "Genetic Code of Human Life Is Cracked by Scientists." *New York Times*, June 27, 2000.

Wadman, Meredith. "Long Covid Is a 'National Crisis.' So Why Are Grants Taking So Long to Get?" *Science,* June 10, 2022. https://www.science.org/content/article/long-covid-national-crisis-so-why-are-grants-taking-so-long-get.

Downloaded from http://direct.mit.edu/books/book-pdf/2476860/book_9780262380393.pdf by guest on 18 November 2024

Waldrop, M. Mitchell. *The Dream Machine: JCR Licklider and the Revolution That Made Computing Personal*. New York: Viking Penguin, 2001.

Wallace, James, and Jim Erickson. *Hard Drive: Bill Gates and the Making of the Microsoft Empire*. New York: Harper Business, 1992.

Warner, Mark. "Bipartisan, Bicameral Bill Will Help Bring Production of Semiconductors Back to U.S." Press release, June 10, 2020. https://www.warner.senate.gov/public/index.cfm/2020/6/bipartisan-bicameral-bill-will-help-bring-production-of-semiconductors-critical-to-national-security-back-to-u-s.

Warsh, David. *Knowledge and the Wealth of Nations: A Story of Economic Discovery*. New York: W. W. Norton & Company, 2006.

Warwick, Ken. "Beyond Industrial Policy: Emerging Issues and New Trends." OECD Science, Technology and Industry Policy Papers no. 2 (2013). https://www.oecd-ilibrary.org/science-and-technology/beyond-industrial-policy_5k4869clw0xp-en.

Watson, Oliver J., Gregory Barnsley, Jaspreet Toor, Alexandra B. Hogan, Peter Winskill, and Azra C. Ghani. "Global Impact of the First Year of COVID-19 Vaccination: A Mathematical Modelling Study." *The Lancet Infectious Diseases* 22, no. 9 (2022): 1293–1302.

Weiss, Charles Jr. "Eurasia Letter: A Marshall Plan We Can Afford." *Foreign Policy* 106 (1997): 94–109.

Weiss, Charles Jr., and William B. Bonvillian. *Structuring an Energy Technology Revolution*. Cambridge, MA: MIT Press, 2009.

Weller, Nicholas, Mahmud Farooque, Michelle Sullivan Govani, and Leah Kaplan. "Blinded by the Frontier." *Issues in Science and Technology*, July 17, 2020. https://issues.org/endless-frontier-act-and-public-values/.

Wessner, Charles. "Entrepreneurship and the Innovation Ecosystem Policy: Lessons from the United States." Max Planck Institute of Economics, Entrepreneurship, Growth and Public Policy Group, Jena, Germany, 2004.

Westerman, George, William B. Bonvillian, Axelle Clchard-Bossuet, Lakshmi Amrutha Killada, John Liu, and Steve Nelson. "MassBridge: Advanced Manufacturing Workforce Education Program—Benchmarking Study: Phase One Report." Massachusetts Institute of Technology (MIT), Office of Open Learning, Cambridge, MA, April 12, 2021. https://openlearning.mit.edu/sites/default/files/inline-files/Benchmarking%20Phase%201%20Report%20%28Final%29.pdf.

Weyant, John Peter, Ernestine Fu, and Justin Bowerstock. *Renewed Energy: Insights for Clean Energy's Future*. Palo Alto, CA: Kauffman Fellows Press, 2018.

White House. "The Biden-Harris Plan to Revitalize American Manufacturing and Secure Critical Supply Chains in 2022." Statements and Releases, February 24, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/.

White House. "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth. 100-Day Reviews Under Executive Order 14017." White House press release, June 2021. https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf.

White House. "Early Signs That Bidenonomics Is Attracting New Foreign Investment in U.S. Manufacturing." Council of Economic Advisors, August 23, 2023. https://www.whitehouse.gov/cea

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/written-materials/2023/08/23/early-signs-that-bidenomics-is-attracting-new-foreign-investment-in-u-s-manufacturing/.

White House. "National Science and Technology Council." n.d. https://www.whitehouse.gov/ostp/nstc/.

White House. "Statement by National Security Advisor Jake Sullivan and Economic Council Director Brian Deese on EXIM Bank's Domestic Finance Initiative." Statements and Releases, April 14, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/04/14/statement-by-national-security-advisor-jake-sullivan-and-national-economic-council-director-brian-deese-on-exim-banks-domestic-finance-initiative/.

Williams, Ellen D. *ARPA-E: The First Seven Years: A Sampling of Project Outcomes*. *Vol. 1*. Washington, DC: Advanced Research Projects Agency–Energy, 2016.

Williams, Ellen D. *ARPA-E: The First Seven Years: A Sampling of Project Outcomes*. *Vol. 2*. Washington, DC: Advanced Research Projects Agency–Energy, 2017.

Williams, Ellen D. *ARPA-E: The First Seven Years: A Sampling of Project Outcomes*. *Vol. 3*. Washington, DC: Advanced Research Projects Agency–Energy, 2018.

Williams, Katherine Broome. *Grace Hopper: Admiral of the Cyber Sea*. Annapolis, MD: Naval Institute Press, 2004.

Wise, Robert, dir. *The Andromeda Strain*. Los Angeles: Universal Pictures, 1971. 2 hrs., 10 mins.

Womack, James P., David T. Jones, and Daniel Roos. *The Machine That Changed the World*. New York: Simon & Schuster, 1990.

World Bank. "GDP Growth (Annual %): 1961–2021." https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG.

World Bank. "Manufacturing, Value Added (current US$)—China, United States." https://data.worldbank.org/indicator/NV.IND.MANF.CD?locations=CN-US.

Yang, Zeyi. "How Did China Come to Dominate the World of Electric Cars?" *MIT Technology Review*, February 21, 2023. https://www.technologyreview.com/2023/02/21/1068880/how-did-china-dominate-electric-cars-policy/.

Yannuzzi, Rick E. "I-Q-Tel: A New Partnership Between the CIA and the Private Sector." *Defense Intelligence Journal* (2007). https://web.archive.org/web/20150905090735/https://www.cia.gov/library/publications/intelligence-history/in-q-tel.

Young, Todd. "Young, Schumer Unveil Endless Frontier Act to Bolster U.S. Tech Leadership and Combat China." Press release, May 27, 2020. https://www.young.senate.gov/newsroom/press-releases/young-schumer-unveil-endless-frontier-act-to-bolster-us-tech-leadership-and-combat-china.

Zambon, Stefano, Giuseppe Marzo, Laura Girella, Mario Abela, and Nicola D'Albore. "A Literature Review on the Reporting of Intangibles." European Financial Reporting Group (EFRAG), Brussels, February 2020. https://www.efrag.org/Assets/Download.

Zhang, Sarah. "The Human Genome Is—Finally!—Complete." *The Atlantic*, June 11, 2021. https://www.theatlantic.com/science/archive/2021/06/the-human-genome-is-finally-complete/619172/.

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